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DEVELOPMENT OF A SONAR OIL TANKER CARGO MEASUREMENT SYSTEM.(U)

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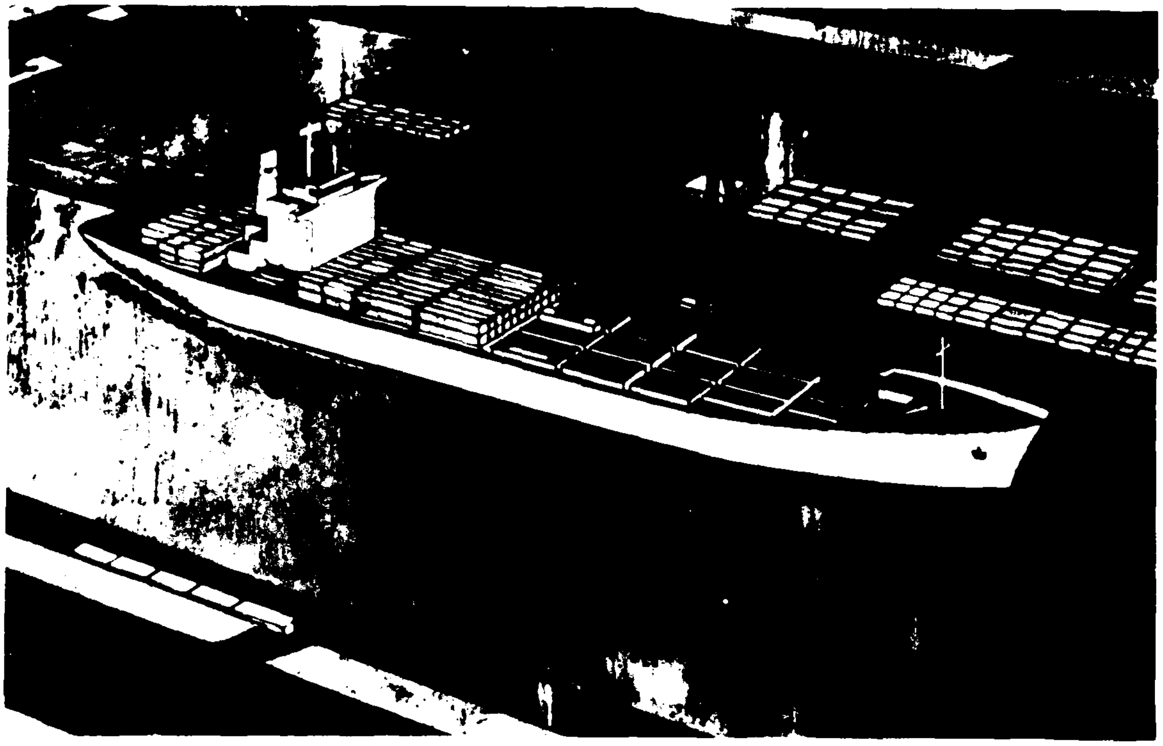

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Maritime Administration

RESEARCH AND DEVELOPMENT

Office of Advanced Ship Operations

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LEVEL II ②

DEVELOPMENT OF A SONAR OIL TANKER

CARGO MEASUREMENT SYSTEM

BY

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The SOTS-T was determined to be feasible for: cargo load level gauging within custody transfer accuracy; operation within a "closed ullage" environment; and pollution control monitoring required by IMCO. The SOTS-T configuration was integrated into a cargo measurement system, and incorporated all of the required measurement functions.

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ABSTRACT

Ocean pollution by oil has received worldwide attention in recent years as a result of concern for environmental damage caused by major oil tanker casualties. Although public attention has focused on tanker accidents, in actuality, the bulk of oil entering the ocean from tankers results from normal tanker operations. Public awareness has initiated international regulations affecting tanker technology and operations, and has influenced pending international maritime law. The development of technology related to oil tankers must, as a result, occur within the context of industry requirements and pertinent international regimes.

This dissertation investigates the developmental sequence for tanker technology through the conceptual design of an acoustic cargo load level gauging system for oil tankers.

A Sonar Oil Thickness Sensor (SOTS) device designed to measure the thickness of oil spilled onto the sea was investigated for adaptation to an oil tanker cargo measurement system. The SOTS-T (oil tanker configuration) utilizes the SOTS operational features of microprocessor control and time gated sampling window, to locate and measure oil/air and water/oil interfaces in cargo tanks and a variety of other oil tanker measurement situations.

The SOTS-T was configured to comply with the developmental constraints of tanker infrastructures, operations, and the international regulations of Intergovernmental Maritime Consultative Organization (IMCO). The implications of pending international law to tanker technology, as contained in United Nations Law of the Sea Conference (UNCLOS III) and international liability organizations, were investigated.

The SOTS-T was determined to be feasible for: cargo load level gauging within custody transfer accuracy, operation within a "closed ullage" environment, and pollution control monitoring required by IMCO. The SOTS-T configuration was integrated into a cargo measurement system, incorporating all of the required measurement functions.

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SYMBOL REFERENCE

A/D	Analog to Digital
b	In-situ Sound Velocity Fixed Distance
c	Speed of Propagation
C	Centigrade
d_i	Distance of Transceiver to Tank Bottom
d_T	Depth of Surface Level
d_W	Depth of water/oil Interface
D/A	Digital to Analog
db	Decible
DI	Directivity Index
DT	Detection Threshold
f	Frequency
F	Fahrenheit
kHz	Kilohertz
MHz	Megahertz
NL	Noise Level
Ns	Self Noise
r_i	Distance from Transceiver to Interface
R	Rayleight Reflection Coefficient
RL	Reverberation Level
SL	Source Level

T_i	Transceiver Station i
TiU	Upper Transceiver at Station i
TiL	Lower Transceiver at Station i
RL	Transmission Loss
TS	Target Strength
V_{pp}	Volt Peak to Peak
μbar	Microbar
λ	Wavelength
ρ	Density

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1. INTRODUCTION

Pollution of the world's oceans by petroleum has become a problem of global concern in the last several decades. World demand has increased the vessel borne transportation of petroleum from areas of production, usually less developed countries, to areas of refining and consumption, usually developed countries. An index of this increase in marine transportation of petroleum is reflected in the world's tanker fleet which has doubled in numbers since 1940 with an eightfold accompanying increase in average vessel size, as shown in Table 1.1.[1]

The increase in transportation and the growth of tanker size has produced tanker accidents which have resulted in catastropic oil spills and focused world attention on marine pollution by tankers. The result has been legislative action and demands for prevention and control of oil pollution.

Legislation has been enacted and further measures proposed on the international level through the Intergovernmental Maritime Consultative Organization (IMCO), a United Nations agency regulating the technical aspects of the design, construction, and operation of oil tankers. The United Nations Law of the Sea Conferences have pending legislation which contain provisions for coastal countries to protect themselves from vessel source pollution within the new "economic zone" which extends usually 200 miles from their coastline and which heretofore has been the domain of the "high seas" with ramifications to the traditional concepts of "freedom of passage."

TABLE 1.1

WORLD OIL TANKER FLEET

Year	Number	Deadweight Tonnage (10^6)	Average Size of Vessel (tons)
1940	1,637	17.58	10,733
1950	2,056	26.96	13,113
1960	3,264	65.78	20,153
1970	4,002	167.94	41,964
1973	4,563	256.72	56,261
1978	3,438	285.61	83,075

The tremendous cost of cleaning up oil spills has motivated international and industrial agreements of liability to clarify and provide funds for the clean up costs.

Consequently the oil tanker industry is currently in a period of transition in response to a world concerned with the prevention of oil pollution of the sea.

Technology directed toward oil tankers must therefore be fashioned and implemented not only with regard to a specific industrial situation, but must be developed within the framework of international regulations, legal implications and economic constraints.

To investigate these developmental constraints a new item of technology was examined for use on oil tankers. An existing laboratory sonar oil thickness sensor (SOTS) device used for the measurement of the thickness of thin oil layers which occur during oil spills was investigated for the feasibility of oil tanker cargo load level measurement and oil/water interface detection. The SOT-T device, hereafter used to denote the oil tanker application, was the vehicle used to activate and analyze the various developmental constraints.

The basic SOTS device was developed several years ago and is now covered by U.S. Patent No. 4,044,606 dated August 30, 1977.[2] A prototype working model of the SOTS based upon a small microprocessor has been developed and built with the support of the Office of Ocean Engineering of NOAA.[3] This working model was used as a guide for the direct scaling to another system applicable to the measurement of large oil thickness as would be the case for the measurement of the amount of oil in cargo tanks of oil tankers.

In simple terms, the SOTS device is an echosounder (fathometer) coupled with a 6800 microprocessor which controls and processes the acoustical echoes reflected from the surface and interface (oil/water) boundaries. In the oil tanker application a transducer would be mounted on the bottom of cargo tanks, slop tank and ballast tanks to measure the depth of the oil or ballast water, oil/water interface, if present, and volume in each tank.

In order to assess the problems, first a review of the oil pollution situation and its relationship to oil tankers is essential. Oil pollution is not a recent phenomenon, but has been known since Biblical times when, according to Crowell,[4] oil seeped from fractured rock formations and reached the shore. He relates that in the early Christian era, the Arabs had developed means of petroleum distillation which were introduced to Western Europe through Spain. Also, Crowell notes the first documented shipment of petroleum, 1539, only forty-seven years after Christopher Columbus, when petroleum was shipped from Venezuela to Spain on board the Spanish Ship, Santa Cruz. The United States shipped its first oil, carried in barrels, to Great Britain in 1861, in the hold of the Elizabeth Watts, a 224 ton brig.

Today the term barrel of oil remains in use. However the size of ships has changed dramatically. Oil is no longer carried in barrels, but is transported in specially designed crude oil carriers which exceed 400,000 dwt. The dramatic growth of tanker size has been a more recent innovation, prompted by political, economic, and technical factors. The tanker of the 1940s was of the T-2 type so prevalent during the Second World War, with a size of about 16,200 dwt.[5] In 1948, a study released by the Society of Naval Architects and Engineers showed that a

50,000 dwt tanker would reduce ton-mile cost to 60% of 12,000 dwt vessel.[6] The advent of the supertanker, larger than 100,000 dwt, became a reality in the 1960s. With the closing of the Suez Canal in 1967, and the much longer voyage around the Cape of Good Hope, it was found more economical to transport a given amount of oil in a single ship than by a number of smaller ships.

The next generation of crude carrier was designated as Very Large Crude Carrier (VLCC) and was in the 200,000 to 400,000 dwt range. This concept was carried further with another class of ship called the Ultra Large Crude Carrier (ULCC) which was greater than 400,000 dwt. With the construction of larger and larger oil tankers came the concomitant risk of damage caused by a single marine casualty.

The first major oil tanker accident to receive world wide publication and thus focus world opinion on oil pollution occurred when the supertanker Torrey Canyon was stranded on the Seven Stones off the west coast of England in March 1967, spilling 117,000 tons of oil.[7] As a result about 100 miles of the Cornwall coastline was damaged, as were the coastlines of Guernsey and northern France. The most recent large tanker spill occurred with the grounding of the supertanker Amoco Cadiz on March 16,1978 off Roscott, Brittany, and its subsequent break up which spilled its entire 216,000 metric ton cargo of light Arabian crude oil and 4,000 tons of its own fuel into the waters and beaches of that French province.[8] It was the worst tanker accident to date, spilling over twice the amount of the Torrey Canyon.

Although tankers receive the greatest public attention and concern, they are not the chief cause of oil pollution in the oceans. A study published in 1975 by the National Academy of Sciences provides the most definitive estimate to date of the sources of petroleum entering the ocean.[9] It is estimated that a total of 6,000,000 tons of oil enter the ocean each year. Tanker accidents and oil well blowouts, which receive the greatest attention, comprise only about 4% of the total and less than 20% of the 1.35 million tons due to tanker transportation. The remaining 80% of the 1.35 million tons result from normal tanker operations such as tank washings, ballast, and other normal procedures which release oil into the sea. The largest share of global oil pollution comes from man's terrestial operations (44%) in the form of discharge of municipal sewage and wastes from coastal industries, including all wastes carried by rivers to the sea. Offshore oil production accounts for only about a third of one percent of the total. The remaining 22% reaches the ocean via the atmosphere (about 10%), from oil seeps on the ocean floor (about 10%), and from ship's accidents not related to oil production. It is estimated by the NSF study that one year's input of petroleum is continually contained in the ocean. This is significant due to the chronic nature of the oil pollution which is considered more deleterious to coastal and estuary biota than actual dosage.

Since about one-fourth of all oil pollution in the ocean is caused by marine transportation, with tankers as the biggest offenders, this is a definitive area for remedial action. Normal tanker operations contribute about 1,000,000 tons of oil into the ocean each year and provide the most favorable area for improvement.

Operational pollution by tankers is in the form of tank washing and ballast operations. Tank cleaning and ballast operations are required for the majority of tanker return voyages since tankers usually return empty for a new load. After unloading, the cargo tanks are cleaned of clingage (oil that adheres to the walls of the tanks), and sludge (residue accumulated on the bottom of cargo tanks). During water washing operations the oil wash water requires disposal at a shoreside reception facility, or decanting and overboard disposal at sea. Clean seawater ballast is taken on board to give the vessel sufficient draft for operation and sea conditions of the return voyage. This clean ballast is pumped overboard in the harbor during the loading operation. Clingage ranges from 0.1% to 0.9% of the cargo capacity, depending on the type of oil and tanker configuration. It is considered to average 0.4% for crude oil.[10] On a typical 250,000 dwt VLCC, between 1900 and 2200 tons of oil residue remain in cargo tanks after unloading.[11]

International regulations eliminating tanker pollution have been promulgated by IMCO through conventions convened for adoption by member nations. Among the regulations adopted at the most recent conference--the 1978 Protocols to the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL 73)--is the provision for Crude Oil Washing (COW) instead of water washing of tanks.[12] The COW method uses cargo oil directed under high pressure to clean the tanks. The previous water wash method created oily water waste for disposal. However, with the crude oil wash, the clingage and other tank residue is pumped ashore with the rest of the cargo, accomplishing both tank washings without oily waste water, and a more economical transfer of cargo. The COW system is to be used in conjunction with the Inert Gas System (TGS) to maintain a nonexplosive environment in the tanks. These regulations are to provide a "closed ullage" system which essentially eliminates overboard discharge of oily water. The COW requirements would apply on the day of the regulations coming into force. The 1978 Protocol date was June 1979 for new tankers over 40,000 dwt, and June 1981 for existing tankers over 40,000 dwt. Implementation of the regulations place the shipowners in a dilemma since the required equipment is to be functioning on the day of ratification. Consequently the need is present for the development of methods and equipment to meet the impending mandatory regulations.

A statement by Stenstrom focuses on the need for cargo level gauging and interface detection systems:

> The "closed ullage" regulations imposed together with the inert gas operation requires a review of the level gauging arrangement, interface detection arrangement in the slop tanks, stripping efficiency and gas sampling arrangement. Many of these requirements are closely linked with COW requirements. Intricate questions come up when one tries to match COW operations with existing in-tank equipment. For instance, level gauging is necessary during the discharge, but cannot be used together with tank washing...[13]

Mr. Hanley of Exxon International Tankers also stated industry's current need for a satisfactory level gauging and interface detection system to meet IMCO regulations.[14] Existing systems for level gauging and interface detection require access to the tanks which is undesirable since the tanks under closed ullage need to be depressurized for access. A system does not yet exist for cargo level gauging and interface detection without access to tanks. Hanley also stated that a significant amount of water is found in the bottom of cargo tanks after a voyage from the Persian Gulf to the United States, and may be either entrained water in the source crude settling out, or water accumulated in the piping. Consequently, for loss control, measurement of this water also requires a solution.

As a result of the above mentioned industrial requirements, the SOTS-T device was formulated to operate in a closed ullage environment, compatible with crude oil washing and in compliance with IMCO regulations.

In addition to industrial requirements, other developmental constraints (enacted or pending) of IMCO, United Nations Law of the Sea, and liability, were investigated. Laboratory testing was conducted to determine the acoustical parameters of oil which influence the design of a particular measurement device. Based upon SOTS capabilities, and the acoustical characteristics of oil, a SOTS-T oil measurement configuration was designed. The potential of the SOTS-T configuration as the basis for a total oil tanker cargo measurement system was investigated.

2. DEVELOPMENTAL CONSTRAINTS

2.1 INDUSTRY

The growth of marine transportation of petroleum has risen to the level where the amount of oil moved per year is presently more than two billion tons/year (40 million barrels/day) around the world.[15] A major portion of this cargo is carried by supertankers, vessels in excess of 100,000 dwt. The advent of the supertanker began in the mid-1950s when influenced by the Suez crisis of 1955, the first 100,000 dwt tanker was put under construction.[16] These larger ships demonstrated the economic advantages of increased capacity and generated a rapid increase in the size of the world tanker fleet. In the mid-1960s the VLCC came into existence with the construction of a 229,886 dwt tanker in 1964.[17] During the 1960s the most frequently ordered VLCC was just over 200,000 dwt.[18] Larger ships followed with the ULCCs, the Globtik Tokyo and Globtik London, 483,684 dwt and 483,960 dwt respectively, constructed in 1973. The world's largest tankers, the sister ships Batillus and Bellamya, 550,000 dwt each, were constructed in 1976.[19]

According to the U.S. Department of Commerce report, "A Statistical Analysis of the World's Merchant Fleet as of December 31, 1977," supertankers of over 100,000 dwt totaled 1074 of the world's fleet of 5333 vessels, or 20% of the tanker fleet.[20] However, in 1977 more than half of the 362 million dwt fleet was comprised of VLCCs and ULCCs indicating that although supertankers comprised only 20% of the fleet in number, they carried most of the cargo. The tanker trade, hence vessel utilization, fluctuate with the production and consumption of petroleum in response to world economic activity. However, the supertanker's position as a dominant vehicle of world oil movement appears to be an established concept of marine transportation. Consequently, a cargo measurement system proposed for oil tankers must consider the special features of supertankers.

It is the immense size of the supertankers which have altered traditional marine concepts regarding navigation and operation usually associated with ocean going vessels. A supertanker of 100,000 dwt is more than 1000 ft in length and 50 ft in draft. A 480,000 dwt ULCC may have a length of 1250 ft, a width of 203 ft and a draft of 90 ft.

The supertanker typically has 15-20 individual tanks formed by bulkheads transverse and longitudinal to the ship's centerline, with each tank having a capacity of 10,000-40,000 tons of oil. The tanks run from near the bow to the engine room in the stern. The stern usually contains the machinery, crew, and navigational space. The supertanker is usually powered by a steam turbine or diesel driven with a single screw. The operational speed is usually 15-16 knots.

The most limiting and dramatic dimension is the deep draft of these ships (60-90 ft) which restricts them to a limited number of ports around the world. Consequently, the supertankers usually follow specific routes between major loading and unloading terminals. The two primary routes are from the Persian Gulf around the Cape of Good Hope to Western Europe, and from the Persian Gulf through the Straits of Malacca to Japan. The various parts of the world where deep draft terminals do not exist, offshore terminals are currently under construction to join the shore facilities with submarine pipelines. Often, as in the Gulf of Mexico and the coastline of southern California where terminals have not yet been built, the supertankers are offloaded at sea. The cargo is transferred to lightering vessels (smaller tankers able to enter port) until either the entire cargo is removed, or the supertanker has reduced its draft sufficiently to enter the port and unload the remaining cargo directly.

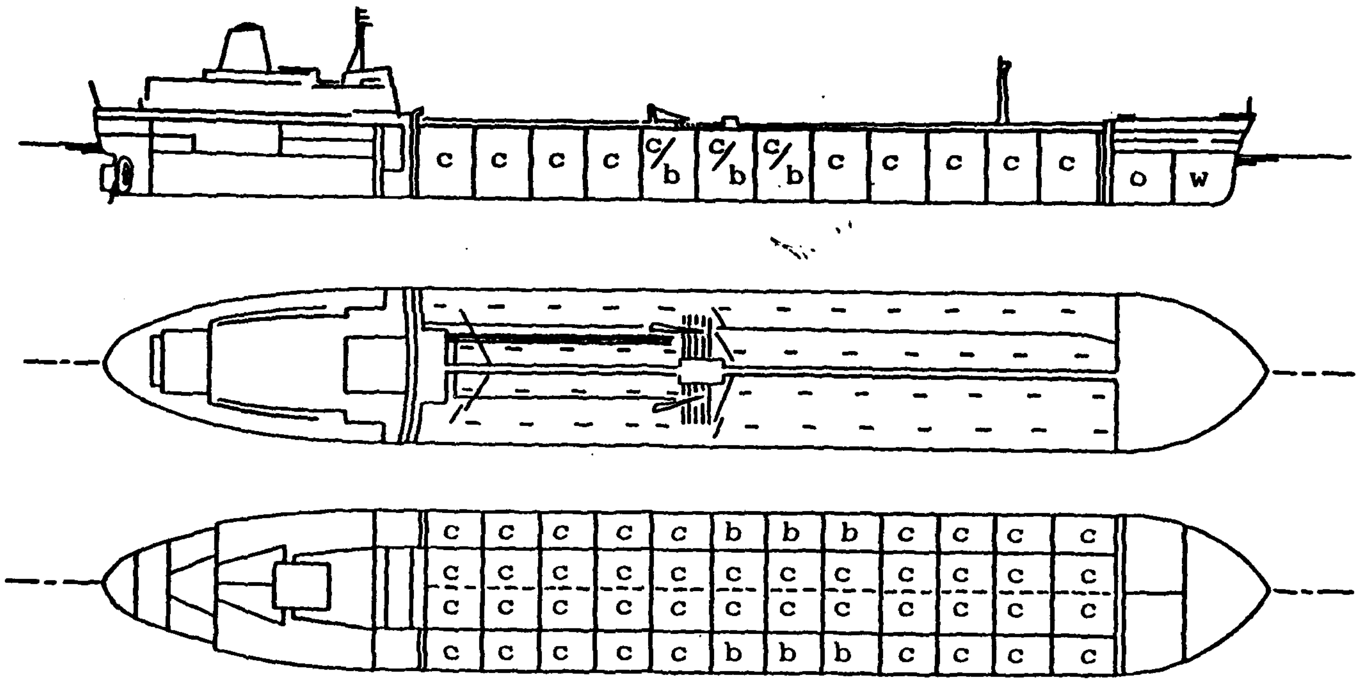
All of these factors--most of which are a result of size--tend to set the supertankers apart from traditional ocean shipping. Since a proposed cargo measurement system must function within tanker constraints, the design and operation of modern tankers were examined.

The prototype vessel of the modern tanker was the steamer Gluckauf, 2,307 tons, launched in 1886.[21] It was conceived and designed specifically for the carriage of oil, and was constructed with cargo tanks from near the bow to the stern machinery compartments. A medium size modern tanker is shown in Figure 2.1.1, indicating the tank locations.[22] The cargo tanks form the major portion of the ship and are constructed to form a structural part of the vessel. Longitudinal strength members with vertical side framing and main transverse members, as in Figure 2.1.2, form the tank compartments which are separated by oiltight transverse bulkheads.[23] Large modern tankers would have two or more longitudinal bulkheads for additional strength and tank separation, as shown in Figure 2.1.3.[24]

In contrast to the flat bottom cargo holds required in dry cargo ships, liquid cargo allows for flexibility by permitting longitudinal and transverse structural members to be present within the tanks. The outside walls of the cargo tank serve to keep the oil in and the sea out, and may form the skin or hull plating of the ship. This is not the case in tankers fitted with double bottoms which form a protective space between the tank and the hull.

The liquid cargo also creates problems, specifically the "free surface effect" within the individual tanks. The free surface of the liquid in the separate tanks act to reduce the metacentric height, GM, thus adversely affecting the ship's stability.

The reduction in GM due to the presence of a free liquid surface is directly proportional to the moment of



(c) Cargo Tanks
(c/b) Permanent Ballast Tanks - port, starboard
(o) Oil Bunkers
(w) Water Ballast

FIGURE 2.1.1 Main Tanks of a Modern Tanker.

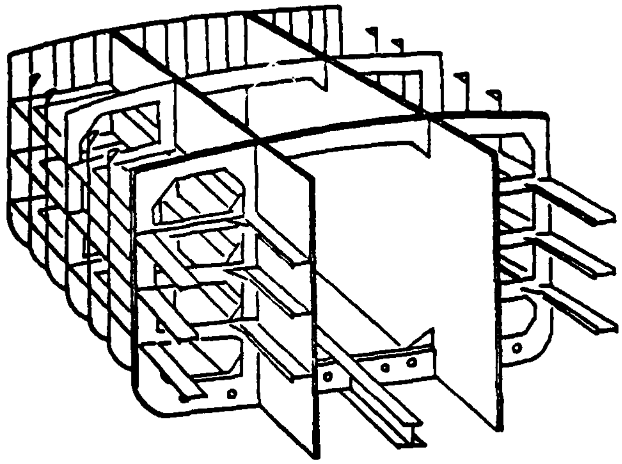


FIGURE 2.1.2 Illustration of a Tanker Hull Showing Vertical Side Framing and Main Transverse Members.

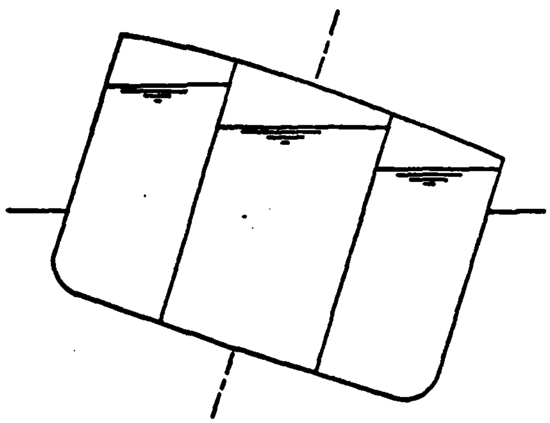


FIGURE 2.1.3 Modern Twin Longitudinal Bulkhead System.

inertia of the free surface liquid area.[25] Consequently, to reduce this effect the free liquid surface in tanks is reduced. In most modern tankers, the free surface effect is minimized by separating the tank compartments with longitudinal bulkheads, as shown in Figure 2.1.3.

Depending upon the design of the tanker, the cargo tanks may be used for ballast. Some new ships, depending upon the trade and regulations, have a number of permanent or segregated ballast tanks.

The outward appearance of an oil tanker distinguishes it from traditional ocean going vessels. The liquid cargo is loaded through pipelines, not hatches. Consequently, the compartment openings can be kept relatively small, which in turn makes it possible to provide very strong covers. With securely fastened openings, a tanker can enhance safety by being loaded lower in the water than a comparably sized dry cargo ship. As a result the freeboard is less, with the weather deck shipping more water than a conventional ship. To provide communications and access along the weather deck, a raised gangway is usually provided which runs from the aft superstructure to the raised bow area. In the case of large tankers the freeboard may be so great that their decks remain clear of water. The longitudinal gangway also serves to act as a structure for carrying the various lines required to service the ship, such as the main steam and exhaust lines to and from deck machinery, lines to cargo heating coils if they are fitted to the bottom of the tanks, compressed air lines, etc.

The trend in larger tankers is to have fewer compartments, hence larger cargo tanks. However, this trend may reverse to minimize pollution risks, in response to pending IMCO regulations which are discussed in a subsequent section. The presence of large cargo tank compartments has restricted the cargo flexibility of these large tankers, however this has not been a problem since most are designed for a specific trade, such as crude oil.

The cargo delivery system may be a direct piping system to each compartment, or, in the case of large tankers, may be a "free-flow" system. The free-flow system allows the cargo to run through valves in the tank bulkheads, rather than through a system of pipelines. The free-flow system usually includes a 10 or 12 inch ring line passing around the ship for stripping individual tanks and facilitating tank cleaning and ballasting, or full discharge in emergencies. When a ship is loading, it is the shore pumps which deliver the cargo to the ship. When it is discharging, it is the ship's pump which transfers the cargo to the shore facilities.

In a free-flow system, during loading or unloading, the ship will develop trim by the stern as the wedge of oil flows toward or away from the bow. This is a consideration to be taken into account in an automatic gauging system.

A simplified drawing of a direct pipeline system is shown in Figure 2.1.4. Note that the pumproom is located

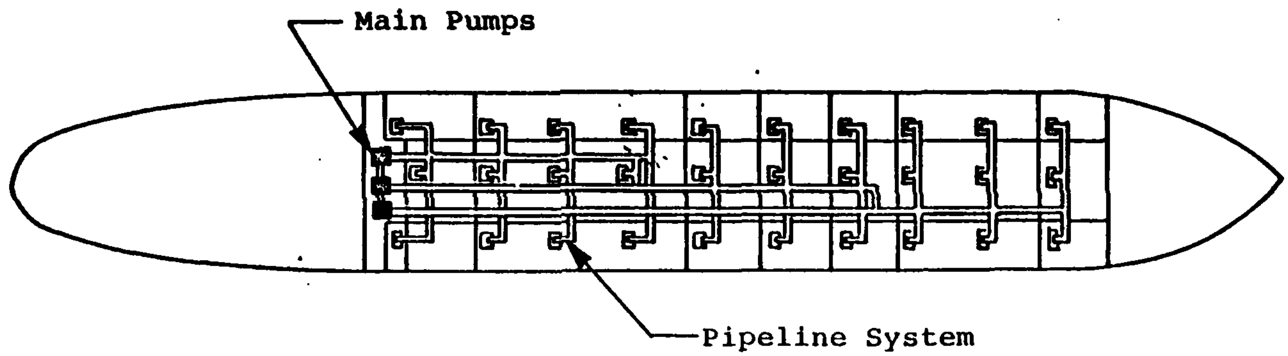


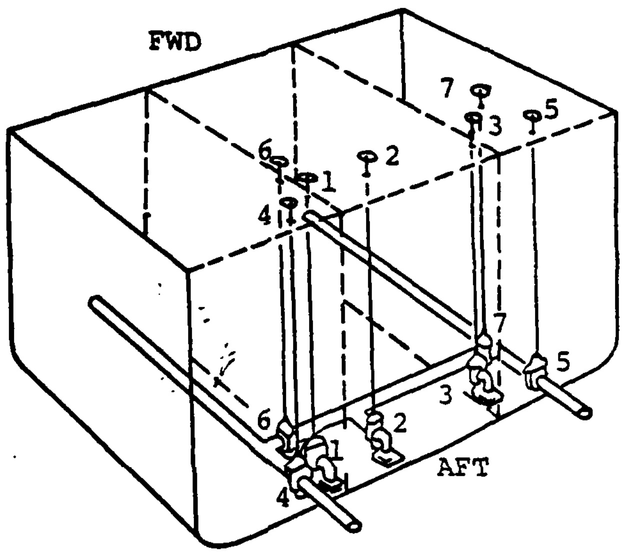
FIGURE 2.1.4 Illustration of a Direct Pipeline System in a Ship with 10 Tanks and 30 Separate Compartments

forward of the engine room.[26] Only the three main centrifugal pumps are shown. The lines may be traced starting at the loading/unloading connection near amidships point. A typical valving system is illustrated in Figure 2.1.5 with a tank configuration using a ring main pipeline system.[27]

Since tankers usually return to a loading port under ballast, one of the prime functions during the return trip is to clean the tanks which will be discharging clean ballast during the loading operations at the terminal harbor. The discharged ballast must be free of oily waste to not pollute the harbor waters. This requires that the tanks be cleaned of any clingage or residue remaining from the previous cargo.

In the modern VLCC the cargo tanks may be fitted with permanently mounted tank washing machines. These machines, whether portable or permanent, direct high pressure jets of water; or, in the case of crude oil washing, direct jets of crude oil. These jets are aimed so that the surfaces not directly struck are washed by the splash from the surrounding structures. The washing machines are used either singly or in groups, depending upon the tank size. The washing machines operate at various heights, usually proceeding from the top of the tank.

The wash liquid, along with the oil and sediment washed off, must be removed progressively as the wash cycle continues. This is done by constant stripping with the stripping pipeline located at the bottom of each tank.



1. Suction Valve
2. Suction Valve
3. Suction Valve
4. Main Valve Port Line
5. Main Valve Starboard Line
6. Port to Starboard Crossover Valve
7. Starboard to Port Crossover Valve

FIGURE 2.1.5 No. 4 Tank in a Ship Fitted with Twin Bulkheads and a Ring Main Pipeline System.

The strippings are discharged into a slop tank when a water wash is used. The slop tank is a tank reserved for receiving the oily waste from tank washings and other operations. The slop tank may be a specially designed compartment for the gravity separation of oily waste from water, or one of the empty cargo tanks. The separated oily waste is transferred to a cargo tank for combination with the next cargo or discharge to port reception facilities.

Sea water, if used as the washing medium, may be delivered to the washing machines either heated or cold. The delivery pumps are of sufficient size to provide the required number of washing machines with a line pressure of 180-200 psi.[28] The number of washing machines used at any one time is dependent upon the capacity of the stripping system. The operation is conducted to strip at least as fast, if not faster, than the water is delivered, so that the tank bottom is kept as dry as possible.

The washing machines are driven by the action of the washing liquid flowing through machines. The liquid flow drives impellers which, by a system of gears, cause the barrel to rotate in the horizontal plane and the jet nozzle in the vertical plane, placing a high pressure jet around the inside of the tank. Basically, each of the various types of washing machines produces this horizontal and vertical motion of the nozzle. The inner structure of the tank is hit with sufficient velocity to dislodge the oil and residue whichever medium is used.

The ballasting for the return voyage is done so that those tanks allocated for clean ballast are left empty for washing during the voyage. If crude oil washing is the method, IMCO regulations require that it be accomplished before proceeding to sea. Usually the ballast within the ship adjusted prior to washing in order to trim the ship for efficient stripping. The ship is then trimmed a maximum by the stern for greater stripping efficiency. In the large crude oil carriers a stripping line delivers the stripping to the aftermost center tank. In water washing, hot water is rarely used (except when the ship is going into dry dock and the tanks must be gas free). Hot water tends to remove the wax skin which adheres to the inner tank structure and is considered a corrosion inhibitor.

The oil industry classifies tankers in two broad categories. These are "clean oil" and "black oil" ships. The clean oil ships usually carry refined petroleum products such as gasoline, aviation fuel, jet fuel and kerosene. The black oil or "dirty" tankers usually carry crude oil, and the heavier refined products such as fuel oil. A ship may be converted, but the practice is to continue in one trade, changing only after a number of years since the conversion requires extensive cleansing. Specialty cargoes, such as lubricating oil which requires particular care and special pumps to avoid contamination, are transported via specially designed carriers.

The division of cargo into clean or dirty is broad and used to ensure that the contamination of lighter grades will not occur from the residues of heavier oils.[29] It is not, however, a true indicator of inherent dangers, so cargoes are also classified by volatility and inflammibility, see Table 2.1.1[30]

TABLE 2.1.1

GRADES OF PETROLEUM PRODUCTS

Grade	Flash Point	Rapid Vapor Pressure	Examples
A (F*)	80°F or below	14 psi or above	natural gasolines, very light napthas
B (F*)	80°F or below	14 psi or above	most commercial gasolines
C (C**)	80°F or below	8.5 psi or below	most crude oils, creosote, aviation gas, grade 115/145 JP-4 jet fuel
D (C**)	above 80°F but below 150°F	...	kerosene, some heavy crude, commercial jet fuels
E (C**)	150°F or above	...	heavy fuel oil, lubricating oils, asphalt

* F = Flammable
** C = Combustible

As shown in the table, virtually all petroleum products are flammable. However, some products like gasoline are extremely flammable, while others such as lubricating oils are relatively safe. The more flammable substances require special precautions. Flammable, as used in Table 2.1.1 is defined as follows:

The flammable liquids are those which give off flammable vapors (as determined by flashpoint from an open-cup tester, as used for test burning oils at or below 80° F [26.7° C]). These are further subdivided into grades A, B, and C on the basis of their Reid Vapor Pressure (a measurement of vapor given off in a closed container heated to 100° F according to ASTM-D323).[31]

Combustible liquids are those which give off flammable vapors at temperatures above 80°F.

From Table 2.1.1 it is evident that generally clean oils are more volatile than black oils. The important exception is crude oil which contains all of the volatile elements to later be refined into the low flash point grades of petroleum products. For electrical safety requirement purposes, crude oil falls into Grade C and D.

In terms of cargo measurement, a liquid can be expressed either in volume or weight. Cubic feet, cubic meters, barrels, gallons, and liters are all measures of volume. The oil industry usually measures by long ton or metric ton. British ships are calibrated in cubic feet, while other nations use liters and metric tons (1 metric ton = 1,000 kilograms = 2,204.6 pounds). The units used on United States ships are given in Table 2.1.2.

TABLE 2.1.2

UNITS OF MEASURE ON AMERICAN SHIPS

1 barrel = 42 gallons

1 ton = 2,240 pounds (also a long ton)

1 net barrel = 42 gallons (adjusted to 60°F)

1 gross barrel = 42 gallons (at actual temperature)

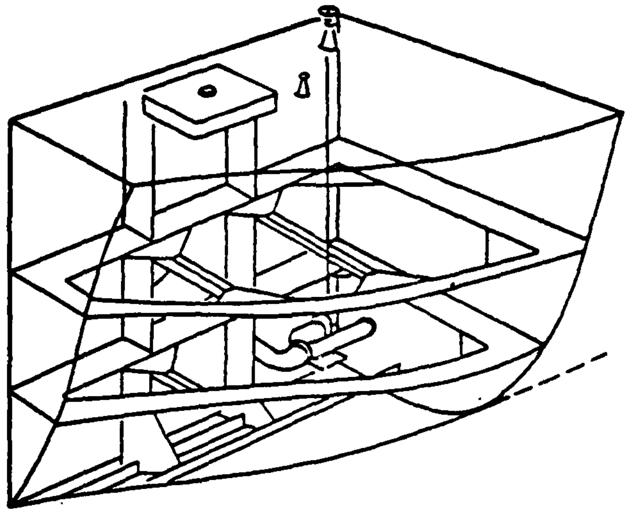


FIGURE 2.1.6 Illustration of a Port Wing Tank Showing the Complexity of Liquid Level Measurement Due to the Presence of Internal Structural Members and Piping.

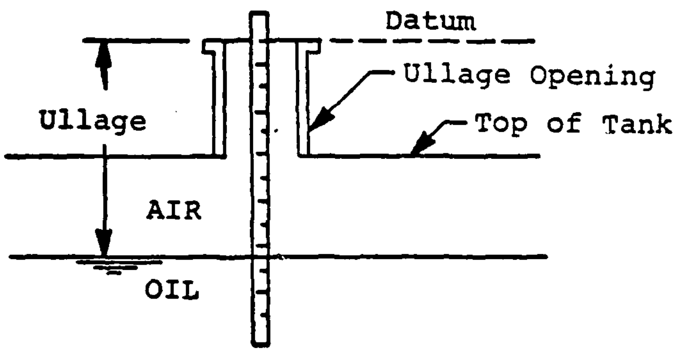


FIGURE 2.1.7 Ullage Measurement of a Cargo Tank.

Cargo measurement, while expressed in various modes, is based upon volume. Once the volume is known, the weight of the liquid can be determined by the use of conversion factors.

Cargo tanks may be of any shape or size, and their measurement is made more complex by the nature of the structure and fittings within the tank. The presence of beams, frames, stringers, pipelines, brackets, and other protrusions, reduces the available space within the tanks. The complexity of the measurement problem is illustrated by Figure 2.1.6, which shows a ship's forward port wing tank, and the structural members and piping within the tank.[32]

Ship's tanks and compartments are premeasured or calibrated during construction, and the calibration tabulated for measurement use. The usual method is to measure the ullage, which is the distance from an above deck datum (the top of the ullage hole in most cases) to the surface of oil in the tank, as in Figure 2.1.7. This ullage measurement is entered in a tank calibration table which gives the amount of liquid in the tank corresponding to the ullage measurement. An extract from a cargo tank calibration table is shown in Table 2.1.3[33]

TABLE 2.1.3

EXTRACT FROM CARGO CALIBRATION TABLE
SAN CLEMENTE CLASS TANKER
NO. 1 WING TANKS

No. 1 Wing Tanks

Ullage	Barrels	Cubic Feet
5'00"	28,312	158,972
1"	28,269	158,730
2"	28,225	158,483
3"	28,181	158,236
4"	28,137	157,989
5"	28,093	157,742
6"	28,049	157,495
7"	28,005	157,248
8"	27,961	157,001
9"	27,918	156,760
10"	27,874	156,513
11"	27,830	156,265
6'00"	27,786	156,018

Another method is to "sound" the tank by lowing a rod or plumb bob to the bottom of the tank, and read the depth off of the tape. When very deep tanks are almost full it is easier to measure ullage than depth, since calibration tables are arranged for either entry.

Ullage may be measured by an automatic tape which is located on the tank. This consists of a tapewell containing the tape, and has a sighted port to facilitate reading. Ships may also be equipped with remote indicating devices monitored in the cargo control room.

The hand tape and plumb bob is considered by some to be the most precise gauging method, and is used on board the Exxon fleet.[34] There are disadvantages, however, for it is both messy and time consuming. It can also be dangerous since it requires the opening of the ullage plug which in turn releases vapors which would otherwise be diverted through the vent system. In addition, on ships that are fitted with inert gas systems, the tank must be depressurized while the hand taping is completed.

Water may be present in loaded cargo tanks, most often after a long voyage. This water which accumulates at the tank bottom may be leftover ballast, tank washings, condensations, or--according to Hanley--entrained water from the source crude, or residual water from the pipeline system. The amount of water present must be accounted for in tank gauging.

A process called "thieving" is used to determine the amount of water present.[35] A graduated metal rod is coated with a litmus paste which changes color when in contact with water, but remains unaffected by oil. The prepared rod is lowered to the bottom of the tank, where the water is settled. Once removed, the location of the color change indicates the height, and therefore the amount of water present.

After each tank has been ullaged and, if necessary thieved, the calibration tables are entered to determine gross barrels or gross tons.

The next step is to correct the ullage for any trim the ship may have. As a rule, a correction is made if the ship is trimmed a foot or more by the head or stern.[36] The trim corrections are most often found on a separate calibration table and the corrections to be applied to the ullage readings are given for each tank, for each foot of trim by the head or stern.

After adjusting the ullage readings for trim, the main calibration tables are entered and the gross tons of cargo in each tank determined.

All petroleum products have a common characteristic: they expand when heated and contract when cooled. Consequently, the effects of thermal expansion must also be taken into account. The oil industry has established a standard temperature of 60°F (15.6°C) from which to calculate the net amount of oil in a tank.

The determination of the net amount of cargo is done using a multiplier obtained from petroleum tables which gives both the correction factor for temperature, and the API gravity, the American Petroleum Institute's equivalent to specific gravity.

The cargo temperature is determined either by direct immersion of a thermometer, or by obtaining the average temperature of the cargo as it passes through a manifold equipped with temperature sensors. According to Marton, the latter method is preferred because it is faster, less messy, and avoids opening of the ullage plugs.[37] As discussed in Section 4, the temperature profile of a cargo tank may vary over a considerable range due to the heat transfer from the cargo (which is usually loaded at an elevated temperature) to the sea during the voyage. This temperature fluctuation within the tank is also a function of the position of the tank. A wing tank with both side and bottom exposure to the sea will transfer heat at a different rate than a center tank with exposure only from the bottom.

The standard for the specific gravity of the cargo is usually determined by the shore installation. Although it is possible to measure both API gravity and specific gravity on board a ship, the shore installation determination is preferred. This is because the shore installation has better facilities, and the use of one figure prevents discrepancies between shoreside and shipboard figures.[38]

API gravity, the industry's standard, is a measurement referential to water. An arbitrary gravity of 10.0 is assigned to fresh water. An API gravity of over 10.0 indicates a product lighter than water, and below 10.0 is heavier. Light products such as gasoline have an API gravity considerably greater than 10.0, but a few products such as heavy fuel oil have values less than 10.0. Table 2.1.4 lists API gravities for some common products.[39]

TABLE 2.1.4

SAMPLE API AND SPECIFIC GRAVITIES

Product	API	Specific Gravity
Motor Gasoline	61.0	0.7351
Kerosene	49.0	0.7839
Gas Oil	39.0	0.8299
Benzene	29.0	0.8816
Heavy Fuel Oil	9.5	1.0035

With the API gravity and temperature determined, the multiplier is extracted from the petroleum tables. This number, when multiplied by the gross volume, yields the volume. The net tonnage of the cargo can then be determined from the net volume by conversion factors.

The tonnage of the cargo must usually be calculated by the ship's officer since tonnages are vital in determining draft, trim, displacement, and stress.

According to Exxon, the acceptable accuracy for custody transfer of cargo is within 0.2%.[40] Exxon, which uses the hand tape method for custody transfer measurement, states that under optimum conditions the hand tape can be read to within 1/8 of an inch. In addition to the already mentioned disadvantage of this method, it is also highly dependent upon experienced personnel. Further, wave action in the tank will complicate the reading of the tape. In these cases the person reading the tape must estimate the true reading on the tape from the excursions of the liquid due to the wave action. The use of the hand tape requires access to the tank. This allows vapors within the tank to escape, and in the case of a tanker fitted with an inert gas system, the tank must be depressurized prior to gauging.

Other measurement systems currently used include a microwave system which is permanently mounted on the top of the tank and transmitts signals which are reflected off the top surface of the liquid. Another type of system operates on the principle of the vibrating wire to detect liquid level. Mechanical float systems are also used which indicate depth by the position of a float.

None of these systems, however, is capable of determining the presence of water in a cargo tank, or of determining the location of water/oil interface in the cargo tanks and slop tanks without access to the tanks. An instrument currently available which can determine the location of a water/oil interface is an acoustical tape. The device has an acoustical sensor located on the end of a hand tape with the ability to detect different density interfaces. It can detect the location of the oil/air and water/oil interface. When the sensor comes in contact with an interface it gives off an audible beeping signal. It operates as a hand tape which determines the ullage measurement and location of a water/oil interface from a reference datum on top of the tank. In order to determine a measurement in the presence of waves, the acoustical tape is lowered until a beeping signal indicates the presence of an interface.

The wave height is then determined by measuring the distance when the device gives off beeps corresponding to the wave crests and wave troughs. The ullage measurement is then the average of the wave crest and trough readings. The disadvantage of this system are the same as for the standard hand tape since it requires access to the cargo tanks and operation by experienced personnel.

As mentioned previously, a measurement of cargo temperature is important due to the thermal expansion of the cargo. The cargo is loaded at a temperature of about 150°F with a maximum of 160-170°F to a minimum of 60-70°F. During the voyage, heat transfer from the cargo to the sea causes both horizontal and vertical temperature stratification. In addition, since oil is a poor conductor of heat, there is a lower temperature layer near the tank bottom, and in the case of a wing tank, near the hull side. Temperature profiles taken on board a tanker are described in Section 4.

Another complication, according to Exxon, is the deflection of the tank. Uncontrollable variables, such as temperature fluctuations of the steel in the ship and loading conditions such as full cargo, partial cargo and variable ballast level, contribute to deflect the sides and bottom of the tanks. Exxon is currently investigating this to determine the total accuracy of the measurement system.

Thus any measurement system must conform to a number of operational and inherent constraints. In the industry the acceptance of a measurement system is largely a function of tradition and maintainability. For these reasons the hand tape currently remains the widely accepted measurement system for custody transfer. Any new measurement system must take into account the presence of temperature gradients, be able to operate in a closed ullage environment, possess acceptable maintainability, and have sufficient advantages to supercede tradition.

In addition to the measurement of cargo for custody transfer, recent pollution regulations adopted by IMCO have modified tanker operations and necessitated liquid measurement requirements during various phases of tanker operation. IMCO and its pollution regulations are examined in detail in Section 2.2.

The IMCO "International Convention for the Prevention of Pollution of the Sea from Ships, 1973" contained regulations for the first time requiring that oil tankers use the Load-On-Top method to retain oily wastes and tank washings for on board processing, and the combination of the separated oily waste with the next cargo. By this method the discharge to the sea of oily residue from tank washings and other sources was greatly reduced.

In the Load-On-Top method, or retention on board as IMCO called it, the oily wastes, dirty ballast water, and tank washings are transferred to a slop tank where the oily residue is allowed to separate from the water by gravity. After separation the water in the slop tank is discharged to the sea providing it is within the oil content limitations specified by the IMCO regulations. The oily wastes remaining in the tank are then transferred to a cargo tank for a combination with the next cargo.

To accurately control the discharge of the water from the slop tank, the location of the water/oil interface must be determined. IMCO regulations require that an interface detector be used in the slop tank to control discharge operations. The 1973 IMCO Convention Regulations 15 (b) stated that:

> Effective oil/water interface detectors approved by the Administration shall be provided for a rapid and accurate determination of the oil/water interface in slop tanks and shall be available for use in other tanks where the separation of oil and water is effected and from which it is intended to discharge effluent directly to the sea.

In order to monitor the discharge of water from the slop tank a measurement system must be capable of detecting the changing water/oil interface as the tank contents are drawn down to the stage where the water discharge is halted and the oil can be pumped to a cargo tank.

The use of crude oil washings became mandatory for new crude oil tankers and certain existing tankers in the 1978 MARPOL Protocol.[42] Regulation 13 (6) called for crude oil washings on every new crude oil tanker of 20,000 dwt and above. Existing crude oil tankers of 40,000 dwt and above, in lieu of being fitted with segregated ballast tanks, may be provided with crude oil washing as specified in Regulation 13 (8).

An important part of the crude oil washing operation is the efficient stripping of the tanks until the bottom is "dry." To verify the effectiveness of stripping and cleanliness for departure, ballast of a tank that has been crude oil washed, paragraph 4.2.10 (ii) of Resolution 15 of the 1978 MARPOL Protocol requires that a measurement be made of the amount of oil floating on top of the ballast. The ratio of the volume of oil floating on top of the ballast to the volume of the tank was not to exceed 0.00085. In this situation a measurement technique is required to measure the thickness of oil floating on the ballast water. The water/oil and the oil/air interface must be located and the thickness of oil determined. Knowing the tank geometry, the volume of oil may be determined from the thickness measurement, and the volume ratio of oil to tank capacity determined.

A suitable indication of the effectiveness of stripping the tank is also required by paragraph 4.4.4 of Resolution 15 of the 1978 MARPOL Protocol which states that:

> Means such as level gauges, hand dipping, and stripping system performance gauges as referred to in paragraph 4.4.8 shall be provided for checking that the bottoms of the cargo tanks are dry after the crude oil washing. Suitable arrangements for hand dipping must be provided at the aftermost portion of a cargo tank and in three other suitable locations. For the purpose of this paragraph "dry" means a small quantity of oil near the stripping suction with the tank dry everywhere else.

The reference to a measurement at the aftermost portion of the tank refers to the practice of effecting stern trim of the ship to facilitate stripping. By trimming the ship by the stern, the liquid is collected near the aftermost portion of the tanks where the stripping pumps can remove the remaining washings. Paragraph 4.4.8, referred to above, states that:

> Equipment shall be provided for monitoring the efficiency of the stripping system. All such equipment shall have remote read out facilities in the cargo control room or in some other safe and convenient place easily accessible to the officer in charge of cargo and operations...

This situation requires a sensor to measure, within centimeters according to Exxon, the wedge of remaining washings to indicate a dry condition after stripping and to display this information at a remote location.

The use of the SOTS device to serve as a measurement instrument in monitoring the slop tanks and crude oil washing operations was investigated in addition to the application of cargo measurement.

Other important constraints on the development of equipment for tankers are reflected in the requirements of applicable standards and international pollution regulations. Both of these constraints have implications for cargo and other measurement applications.

The next section deals with standards which apply to the design, construction and operation of tankers.

2.2 STANDARDS

The operation of vessels upon the jurisdictional waters of a nation are usually contingent upon compliance to certain standards of design, construction and operation. The United States Code of Federal Regulations, for example, contains regulations for shipping under Title 46, with special regulations for oil tankers.

The application of the SOTS-T system to oil tankers was required to conform to applicable regulations.

Federal regulations apply for both United States flag vessels, and foreign flag carriers navigating United States waters. All tank vessels are required to possess a valid certificate of inspection verifying that the vessel has complied with the applicable regulations. United States flag vessels are required to be designed, constructed and operated according to specific provisions of the federal regulations and are issued a certificate of inspectionin the normal sequence of approval for registry. Foreign flag carriers operating in United States waters may be issued a certificate of inspection by the United States, or may possess a certificate recognized by the United States under certain conditions. Federal regulations state that:

> ...a vessel of a foreign nation having inspection laws approximating those of the United States, together with reciprocal inspection arrangements with the United States and which has on board a current valid certificate of inspection by its government, in either case...[43]

are considered to possess a certificate recognized by the United States for navigation in United States waters.

Vessel design and construction is usually in accordance with recognized classification societies. Classification societies are private organizations which provide standards and inspection of compliance for ship design, construction and operation. Vessels are graded or "classed" according to the character of the vessel for its purpose. Classification of a vessel is required for registry and insurance purposes.

The United States regulations require conformance to the "Rules for Building and Classing Steel Vessels" issued by the American Bureau of Shipping (ABS). Other pinciple classification societies are Lloyd's registry, London; Bureau Veritas, Paris; British Corporation, Glasgow: Germanischer Lloyd, Berlin; Norske Veritas, Oslo; Registro Italiano, Rome; and Japanese Maritime Corporation (Teikodu Kaiji Kyokai), Tokyo.[44]

In addition to the requirements of the American Bureau of Shipping, other specifications, standards and codes are referred to in the federal regulations such as the National Fire Protection Association, the National Electric Code, etc.

Equipment on board a vessel is classified according to its function and location for safe operation. An oil tanker transports flammable cargo; and, depending upon location, equipment is classified and approved for use in hazardous locations. A Class I location is defined as one in which flammable gases or vapors are or may be present in the air in quantities sufficient to produce explosive or ignitable mixtures.[45] Crude oil is the source for all of the refined combustible petroleum products and the vapors continually released from crude oil are flammable. Consequently, cargo tank areas on oil tankers are classified as Class I hazardous locations. The Class I location is further divided into Divisions depending upon the probable occurrence of flammable gases or vapors. Crude oil tanker cargo areas are included in Class I, Division 1 locations in which hazardous concentrations of flammable vapors occur continuously, intermittently, or periodically under normal operating conditions, repair, maintenance, leakage or faulty operations of equipment.[46]

According to federal regulations, "this classification would usually include locations such as cargo tanks, cargo pumprooms, cofferdam areas, and in some cases, open deck areas..."[47]

Since the explosive characteristics of an inflammable gas or vapor depend upon the material, the mixture in a Class I hazardous location is further divided in Groups A, B, C, and D according to explosive qualities. Crude oil is included in Groups C and D. Consequently, the classification of a cargo tank location would be Class I, Division 1, Group C, D, hazardous location.

The ABS classification rules include a section for

"Vessels Intended to Carry Oil in Bulk." A classification of +A1 Oil Carrier is assigned to vessels designed to carry oil in bulk. The term "oil" is defined as, "petroleum products having a flash point at or below 60°C (140°F), closed cup test, and specific gravity of not over 1.05."[48] ABS states that electrical instrumentation including

> ...liquid-level gauging devices may be installed in the tank or in enclosed spaces immediately adjoining the cargo oil tanks provided such equipment has been tested and certified by a competent independent testing laboratory as being safe for the hazardous location in which it is installed.[49]

Federal regulations state that "...no electrical equipment may be installed in cargo tanks except approved intrinsically safe equipment..."[50]

The term "intrinsically safe" is defined in federal regulations. It is stated that "the term 'intrinsically safe' when used with instruments and equipment or wiring shall mean such instruments and equipment or wiring that is incapable of releasing thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous mixture in its most easily ignited concentration."[51]

The ABS also states that "electrical equipment of the intrinsically-safe type only may be installed in cargo rooms, 'tween decks, cofferdams, enclosed spaces immediately adjoining the cargo tanks, or any similar spaces where vapor or gas may normally be expected to accumulate."[52]

The open deck area near cargo tanks is classified as a hazardous location. The rules of ABS state that:

> ...equipment installed within zones on the open deck over all cargo tanks (including all ballast tanks within the cargo tank block) and to the full width of the vessel plus 3 m (10 ft) fore and aft on the open deck up to a height of 2.4 m (8 ft) is to be of an approved explosion-proof type or is to be intrinsically safe. In addition, any electrical equipment within 3 m (10 ft) of any cargo oil tank outlet or vapor outlet is to be of an approved explosion-proof or intrinsically-safe type.[53]

Since the SOTS-T system would require electrical equipment within cargo tanks, and a cabling system located on deck, the system would be required to conform to the specifications for intrinsic safety.

Standards for evaluating equipment for intrinsic safety are contained within the National Fire Protection Association (NFPA) publication 493, entitled "Intrinsically Safe Apparatus for Use in Division 1 Hazardous Locations 1978."[54] Independent testing laboratories also provide intrinsic-safety standards and perform evaluations and testing of equipment for certification as intrinsically safe.

The intrinsic-safety analysis of the SOTS-T equipment is contained in Section 3.

2.3 INTERGOVERNMENTAL MARITIME CONSULTATIVE ORGANIZATION

The internationally recognized organization which addresses maritime issues is the Intergovernmental Maritime Consultative Organization (IMCO), a specialized agency of the United Nations. In response to international concern about tanker pollution, IMCO has broadened its focus and promulgated regulations governing tanker design and operation.

The creation of IMCO began in June of 1946 when the United Nations Economic and Social Committee approved recommendations for the inception of a permanent international organization to coordinate maritime affairs. Two years later, at the United Nations Maritime Conference in Geneva in 1948, the convention creating IMCO was approved.[55]

IMCO had its first official meeting on January 16, 1959 when the requisite twenty-one states (including seven which had more than one million gross tons of shipping registered) had become parties to the convention.

Initially, the maritime nations resisted the formation of IMCO and probable regulatory infringement on international shipping. However, during the 1950s it became apparent that oil pollution from tankers was a critical problem. The accelerated development of the chemical industry, and the problems of hazardous cargos, further reinforced the inevitability of international regulations.[56]

Conventions focusing on oil pollution by tankers actually began with a 1926 International Conference on the

Prevention of Pollution of the Sea by Oil, held in Washington, D.C. James Reynolds of the American Institute of Shipping stated, in a 1977 Senate hearing on tanker safety, that the IMCO International Conference for the Prevention of Pollution from Ships 1973, actually had its beginnings in this earlier conference.[57]

At present, the only international regulations in force are those contained within the 1954 International Convention for the Prevention of Pollution of the Sea by Oil, referred to as the 1954 Convention.[58]

The 1954 Convention came into force on July 26, 1958, twelve months after the date on which not less than ten governments had become parties to the Convention which included five governments of countries which have not less than 500,000 gross tons of tanker tonnage.[59] Consequently, the Convention came into force four years and two months after its adoption, when France ratified the Convention on July 26, 1957. The five countries which by national ratification brought the 1954 Convention into force were: the United Kingdom, Sweden, Denmark, Norway and France. Since the approval process requires the legislatures of the member nations to ratify IMCO conventions, years pass before international agreements are finalized.

Since the 1954 Convention, there have been a number of pollution prevention conventions adopted by IMCO (as yet unratified), imposing more restrictive regulations. The 1954 Convention was amended in 1962, 1969, and 1971. Then, in response to the increased magnitude of environmental damage caused by oil tanker casualties, and a recognition of additional harm to the marine environment from other hazardous cargo, the 1954 Convention was superseded by the International Conference on the Prevention of Pollution from Ships, 1973, referred to as MARPOL 1973.[60] The most recent convention was the International Conference on Tanker Safety and Pollution Prevention, 1978, which adds Protocols to MARPOL 1973.[61] This latest conference is also referred to as the 1978 Protocols or the 1978 TSPP.

Initially IMCO was not established to deal with the prevention of pollution of the sea by ships. Its province was--and remains--a broad range of maritime matters as illustrated by Silverstein's list of conventions and amendments from 1959 to September 1972:[62]

1. International Conventions for the Safety of Life at sea.
    a. 1966 Amendments
    b. 1967 Amendments
    c. 1968 Amendments
    d. 1969 Amendments
    e. 1971 Amendments

2. International Regulations for Prevention of Collisions at Sea, 1960

3. International Convention for the Prevention of Pollution of the Sea by Oil, 1954, as amended in 1962
    a. 1969 Amendments
    b. 1971 Amendments

4. Convention on Facilitation of International Maritime Traffic, 1965

5. International Convention of Load Lines, 1966
    a. 1971 Amendments

6. International Convention of Tonnage Measurement of ships, 1969

7. International Convention Relating to Intervention on the High Seas of Oil Pollution Casualties, 1969

8. International Convention on Civil Liabilities for Oil Pollution Damage, 1969

9. Special Trade Passenger Ships Agreement, 1971

10. Convention Relating to Civil Liability in the Field of Maritime Carriage of Nuclear Material, 1971

11. Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1971

The time consuming and delaying process of ratification has been given special IMCO emphasis. The time required for a convention to come into force is governed by various factors. IMCO has identified the major ones as:[63]

a. conditions for the entry into force as prescribed by the convention;
b. technical and administrative implications involved in the implementation of the convention;
c. legislative procedures in individual countries;
d. the will of the governments.

Most of the technical conventions include (in the entry into force conditions) a minimum figure for the aggregate tonnage, or number of ships, owned by member states ratifying the convention. Common conditions in recent technical conventions are the combination of minimum number of states (15-25), and minimum total tonnage (50-60%) of the world's merchant fleets.

The MARPOL 1973 contains a number of complex technical provisions, which IMCO states, "is the main reason why the 1973 Convention has not been ratified by any of the maritime nations."[64]

The 1978 TSPP Conference adopted a resolution to bring the 1978 Protocol (which incorporates the 1973 MARPOL Convention) into force in June 1981, and urged member governments to enact appropriate legislation without waiting for the target date.

To gain a perspective on vessel source pollution regulations, the 1954 Convention is examined next, followed by the provisions of MARPOL 73 and the 1978 Protocols.

The 1954 Conventions states that all seagoing ships, registered by the contracting parties, of 500 gross tons or more, shall not discharge any oil mixture which fouls the surface of the sea within 50 miles of land with the exception that within special prohibited areas, no discharge is allowed.[65]

"Oil" is defined to mean crude oil, fuel oil, heavy diesel oil, and lubricating oil; and an oil mixture shall be construed accordingly. Under Article II, for the purpose of discharge, the oil in an oil mixture shall be less than 100 parts of oil in 1,000,000 parts of the mixture or 100 ppm and this mixture shall not be deemed to foul the surface of the sea.

Violation of the provisions for discharge of oily mixtures into the sea is an offense punishable under the laws of the territory or country in which the ship is registered, according to Article III.3.

The "prohibited zone" specified in Annex A, include areas of the Adriatic, the North Sea, the Atlantic and certain areas around Australia. The designation of prohibited zones reflects the concern for areas particularly sensitive, or exposed to oil pollution. In most cases the prohibited zones have increased the distance from land where oily discharges are prohibited, and are in the range of 50-150 miles. The prohibited zones are subject to later revision by formal declaration from the country involved, with certain time provisions for implementation.

Every tanker is required to maintain an Oil Record Book, by Article IX, authenticating ballast operations, cleaning of cargo tanks, settling in the slop tanks, discharge of water, and disposal of oily residue from slop tanks and other sources as specified in Annex B. The oil record book may be inspected by a competent authority from any of the contracting government's territories, and certified copies made available which shall be admissible in any judicial proceedings.

A number of later amendments were made to the original 1954 Convention. The first such amendment was that of 1962, adopted in London in April of 1962.[66]

Among the provisions of the 1962 Amendments was the redefinition of the terms of Article I. The term "discharge" was defined to mean the escape of oil or oily mixture, however caused. The definition of "ship" was now to include any seagoing vessel, including floating craft, self-propelled or towed, making a sea voyage. This broader definition includes seagoing craft, such as barges, with other than the traditional ship shape conventionally associated with the term ship. A "tanker" was given a more definitive meaning and meant a ship which could, by the definition of ship be a barge, in which the greater part of the cargo space is constructed or adapted for liquid cargo in bulk and which is not, for the time being, carrying a cargo other than oil in that part of the cargo space. This was in response to the increasing use of oil-bulk-oil (OBO) carriers or combination carriers which are designed to carry bulk commodities other than oil, such as ore.

Article II which dealt with ships that are exempt from the Convention, such as whaling and naval ships, was amended to exempt tankers under 150 gross tons.

New ships of 20,000 gross tons or more, for which the building contract was placed on or after the date the Convention came into force, were prohibited from discharging any oil or oily mixtures whatsoever. However, for these new ships, if the master deemed that special circumstances governed it was not reasonable or practical to retain the oil or oily mixture on board, discharge was allowed under the provisions applicable to existing tankers.

To ensure that equal enforcement would be applied, Article VI was modified by stipulating that any punishment given by the territory of the country in which the violating ship was registered would not be less than that which would be imposed by the participating country in which the violation took place.

The carrying of water ballast in oil fuel tanks was to be avoided if possible. An addition to Article VII, which deals with the provisions for preventing diesel oil and fuel oil from entering the bilges, made this change.

The provisions for providing reception facilities, by Article VIII, was strengthened by requiring that all oil loading terminals and ship repair ports be provided with residue and oily waste reception facilities. This provision is a result of prohibiting the residue from cargo tanks from being discharged overboard. It provides for the residue to be pumped to a reception facility at the loading terminal.

The definition of prohibited zone was modified. The prohibited zone was to be measured "from the nearest land" which was defined to mean from the baseline from which the territorial sea of the territory in question was in accordance with the Geneva Convention on the Territorial Sea and the Contiguous Zone, 1958.[67] In addition, a longer list of prohibited zones was added with most having a prohibited zone of 100 miles or more from the nearest land.

A number of resolutions were included in the 1962 Amendments. IMCO, recognizing the lengthy time required for contracting governments to ratify the convention amendments, called for interim measures to reduce vessel source pollution by Resolution 3, "Interim Measures Pending the Coming into Force of the Convention" in which governments were immediately urged to: (1) make arrangements for the prevention of escape of fuel oil and heavy diesel oil into the bilges which are discharged into the sea without being passed through an oily water separator; (2) provide reception facilities in port where they are not now adequate; and, (3) follow the other principles of the convention as far as may be reasonable.

The discharge of oil mixtures from tankers was addressed in Resolution 4:

> RESOLVE
> (1) that in addition to observing the requirements of the present Convention, all tankers should, whenever it is reasonably practicable to do so, avoid altogether the discharge into the sea of oily mixtures and should retain them on board for discharge into shore reception facilities;
> (2) that the terms of this resolution should be specially brought by the Contracting Governments to the attention of the owners and masters of the tankers, oil companies, port authorities and ship repairers.

This resolution coincided with the industry's development of the LOT method of waste retention, in which oily wastes from tank washings and other sources are collected, separated from water in the slop tank, and combined with the new cargo.

IMCO called for the "Preparation of Manuals and Guidance for the Avoidance of Oil Pollution" by Resolution 11 to provide standard operating guidelines for the ship's personnel to avoid the occurrance of oil pollution during normal oil transfer operations and to comply with convention standards. The resolution further states "that Governments should ensure that the syllabuses of examination for Certification of Competency for Navigating and Engineering Officers cover the practices and the use of equipment by which pollution of the sea can be avoided." Thus, pollution prevention was encouraged to become part of the qualification requirements before ship's officers would be authorized to operate a ship.

On October 21, 1969, additional amendments were made to the 1954 Convention.[68] The 1969 Amendments withdrew the provisions in Article II wherein the rate of discharge for tankers was 100 parts of oil per 1,000,000 parts of the mixture, instituted in the 1962 Amendments. However IMCO retained this criteria for ships other than tankers. For tankers the oily discharge mixture was redefined in terms of an instantaneous rate of discharge not to exceed 60 liters per nautical mile while the ship was enroute. The restriction of 60 liters per mile was also applicable to ships other than tankers. Consequently, other ships were required to meet both provisions for discharge: 60 liters per nautical mile and a maximum concentration of 100 ppm. In addition, Article III further stated that on ballast voyages the total quantity of oil discharged not exceed 1/15,000 of the total cargo carrying capacity. For a typical VLCC of 250,000 dwt this would amount to only about 17 tons of oil per ballast voyage. This was a substantial reduction considering that oily mixtures from tank washings prior to and during a ballast voyage could be as high as 1900-2200 tons of residue retained in a typical 250,000 dwt VLCC after unloading.[69] This restriction reflects the success of the industry's LOT or Retention-

On-Board method instituted in the 1960s.

The discharge of ballast from a cleaned cargo tank, as during loading, was limited by Article III such that effluent "if discharged from a stationary tanker into clean calm waters on a clear day, would produce no visible traces of oil on the surface of the water..." This was an obvious provision to set a quantative criteria for the prevention of pollution of the loading port waters by tankers when they discharge their "clean ballast" while taking on new cargo.

The last source of sediment discharge was eliminated by the deletion of paragraph (c) of Article IV which had allowed the residue resulting from the purification of fuel oil or lubricating oil to be discharged without restriction. As a result, by the 1969 Amendments all sources of sediment discharge, unpumpable sediment from cargo tanks, and residue from the purification of fuel oil and lubricating were prohibited.

IMCO adopted a resolution on October 12, 1971[70] to encourage implementation of the 1969 Amendments, since certain governments were enacting legislation to implement the 1969 Amendments prior to their entry into force. IMCO advocated that governments give legal effect to the 1969 Amendments before they would come into force internationally, and that governments "accept such items as the oil record book, reports and other documentation, produced by ships of other countries, implementations of the 1969

Amendments."

IMCO again amended the 1954 Convention in 1971.[71] An annex was added to the Convention which established construction standards for new tankers based upon ship dimensions. The standard specified oil cargo tank sizes and location, to limit the amount of oil outflow which would occur in the case of a tanker grounding or collision.

The grounding of the Torrey Canyon on March 18, 1967 prompted the British government to call for an emergency meeting of the IMCO council to consider changes in maritime law and practice. This in turn lead to the call for a new convention, and resulted in the adoption of the International Convention for the Prevention of Pollution from Ships, 1973 (MARPOL 73).[72]

In response to the harmful pollution of the sea by substances other than oil, MARPOL 73 provided regulations for the prevention of pollution by additional noxious or hazardous cargo. These new regulations contained provisions for the prevention of pollution by (1) noxious liquids; (2) harmful substances carried in packaged form, freight containers, portable tanks or road and rain tank cars; (3) sewage from ships; and, (4) garbage from ships.

In February 1978 another international conference was convened which modified the 1973 Convention. The 1978 conference was called in response to a request for further regulations, by the United States, which had experienced a series of tanker accidents during the winter of 1977.

The 1978 conference was entitled the International Convention on Tanker Safety and Pollution Prevention, 1978, and included the "Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, 1973."[73] This conference was referred to as either the 1978 Protocol or the 1978 TSPP in the literature, and is MARPOL Protocol in the text of the Protocol. For the purposes of this investigation the term 1978 Protocol is used.

Since the provisions of MARPOL 73 and the 1978 Protocol are, by Article I of the 1978 Protocol, to be "read and interpreted together as one single instrument," and since the MARPOL 73 Convention has not yet received any ratification from maritime nations, they are examined together in this investigation and referred to as the Convention. Only oil pollution provisions of the Convention were examined.

In general, the Convention follows a format in which the Articles pertain to administrative and implementation provisions, and the Regulations contained in the Annexes, are for various types of cargo. The 1978 Protocol was limited to changes in the regulations pertaining to oil tankers and oil pollution, as contained in Annex I.

"Hazardous substance" was defined in Article 2 as any "substance, if introduced into the sea, is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or the interface with other legitimate uses of the sea, and includes any substance subject to control by the present Convention." "Oil" was classified as a hazardous substance, and its definition was broadened by Regulation 1 (1) to mean "petroleum in any form including crude oil, fuel oil, sludge, oil refuse and refined products (other than petro-chemicals which are subject to the provisions of Annex II of the Present Convention)..." "Crude oil" was defined by Regulation 1 (28) to mean any "liquid hydrocarbon mixture occurring naturally in the earth whether or not treated to render it suitable for transportation..." and includes crude oil which has had certain distillate fractions removed or added.

An "oil tanker" by Regulation 1 (4) was defined to mean a ship constructed or adapted to carry oil in bulk and included combination carriers and product carriers when they are carrying oil as cargo or as part of the cargo in bulk.

The oil pollution provisions of Annex I apply to all ships with certain exceptions such as a minimum amount of oil carried, or would be the case with combination carriers and exemptions for any new type of vessel such as a hydrofoil or submarine oil tanker where Annex I provisions would not be practical or reasonable.

The control of the discharge of oil or oily mixtures is specified by the provisions of Regulation 9. An oil tanker may not, in general, discharge any oil within a special area, within fifty miles of land, or when not enroute. Discharge, when outside the areas specified above and while the ship is enroute, are limited to an instantaneous rate of discharge not to exceed 60 liters per nautical mile and the total quantity of oil discharged cannot exceed 1/15,000 of the total cargo for an existing tanker nor 1/30,000 of total cargo for a new tanker. With the exception of new tankers the discharge criteria has not been changed from that currently in force within the Amendments to the 1954 Convention. In addition, during discharge the tanker must have in operation an oil discharge monitoring and control system and a slop tank arrangement which meets the provisions of the Convention.

For ships over 400 gross tons other than oil tankers and for the discharge of machinery space bilges, except for cargo pump room bilges of an oil tanker, no discharge may be made within a special area, within 12 nautical miles, nor when the ship is enroute. Discharge when a ship is enroute and outside the special areas was limited to effluent with an oil content less than 100 ppm. In addition, the ship must have an operating oil monitoring and control system, and certain other pollution control equipment.

Reception facilities, by Regulation 12, are required at all ports and terminals when crude oil is loaded in which the incoming tanker has arrived from a ballast voyage of less than 72 hours and less than 1,200 nautical miles.

This provision reflects the limitation of the Load-On-Top method where at least 72 hours, or a 1,200 mile voyage are necessary to effect gravity separation of oil and water in the slop tank. Consequently, where the ballast voyages are too short to effectively use the LOT method the tank washings and other residues must be retained on board and discharged to shore reception facilities. Also, all ports and terminals in which oil other than crude oil in bulk are loaded at an average of more than 1,000 metric tons per day are required to have reception facilities. Reception facilities are also required at shipyards, tank cleaning facilities, and for terminals which handle ships which cannot discharge oily wastes according to other provisions of the Convention.

Retention on board, or LOT, is mandatory for oil tankers of 150 gross tons and above, with certain exceptions. For oil tankers less than 150 gross tons, any oily wastes must be retained on board and discharged to reception facilities. Any tanker which engages exclusively in voyages of less than 72 hours, within 50 miles of land, and does not hold a valid certificate was required to retain all oily wastes on board and discharge to reception facilities.

For the first time, the MARPOL 73 Convention, by Regulation 13, required that new oil tankers over 70,000 dwt be provided with segregated ballast tanks. The 1978 Protocol revised the new oil tanker size to include new crude oil tankers of 20,000 dwt and above, and new product tankers of 30,000 dwt and above. A "new oil tanker" was redefined by the 1978 Protocol to mean an oil tanker for which the building contract was placed after June 1, 1979;

or in the absence of a building contract, had the keel laid after January 1, 1980; had a delivery date after June 1, 1982; or had undergone a major revision. A tanker constructed with segregated ballast was required to have sufficient segregated ballast capacity to complete ballast voyages without using any of the cargo tanks for ballast, except under emergency conditions. However, new crude oil tanks may carry additional ballast in cargo tanks if they have been crude oil washed. The requirement for crude oil washing was instituted in the 1978 Protocol for the first time. Crude oil washing of cargo tanks is required in all new crude oil tankers of 20,000 dwt and above.

Existing crude oil tankers of 40,000 dwt and above are required to be fitted with segregated ballast tanks or to install crude oil washing equipment. However, the existing crude oil tankers may, in lieu of segregated ballast or crude oil washing, operate with dedicated clean ballast tanks for a specified period of time. The extended period of time was for two years beyond the entry into force of the 1978 Protocol for crude oil tankers of 70,000 dwt and above. For crude oil tankers of 40,000 dwt and above, but below 70,000 dwt, the extended period was until four years after entry into force. Existing product tankers of 40,000 dwt and above were required to be fitted with segregated ballast tanks or use dedicated clean ballast as specified for product tankers. Tankers using dedicated clean ballast were required to have an oil content meter to verify that contamination of oil has not occurred.

Special provisions for existing tankers engaged in specific trades are contained within Regulation 13 (c) of the 1978 Protocol. These specific trades include trade between ports of the same country, voyages within a special area or withim limits defined by IMCO. These special trade requirements were included to accommodate domestic shipping and shipping special areas. In essence, all ships in specific trades are required to retain all oily wastes, from whatever source, on board and discharge them to reception facilities.

The MARPOL 73 Convention instituted the requirement for survey, issuance of certificates of compliance called the International Oil Pollution Prevention Certificate, and inspections to ensure compliance with the provisions of the Convention. The 1978 Protocol further modified these requirements as contained in Regulation 4.

Every oil tanker of 150 gross tons and above, and, every other ship of 400 gross tons and above, were required to have surveys, certificates of compliance and be subject to unscheduled inspections. Initial surveys were to be conducted for each ship with periodic resurveys at intervals not to exceed five years to determine that "the structure, equipment, systems, fittings, arrangements and material fully comply with the requirements of..." the annex to the Convention.

The officer of the flag state, or recognized surveyors are empowered to carry out the surveys. Unscheduled inspections of ships were required by the Convention to be conducted by officers of the flag state, or recognized surveyors by other parties of the Convention as approved by the flag state. Unscheduled inspections are not necessary if the flag state elects to have annual surveys.

A surveyor has the power to require repairs to a ship if it does not meet the provisions of the Convention. A surveyor can carry out inspections at the request of a Port State. The surveyor can have the ship detained until repairs are effected if it cannot proceed to sea without threat of harm to the marine environment.

IMCO regulations reflect international concern for the prevention of oil pollution from ships. The regulations provide international standards and enforcement procedures, and influence national legislation regulating international traffic in national waters.

An understanding of IMCO and its impact on tanker technology was considered necessary in developing equipment for oil tankers.

The technical provisions of IMCO directly applicable to liquid level measurement requirements were discussed in Section 1, and are incorporated into the SOTS-T system as described in Section 5.

2.4 UNITED NATIONS LAW OF THE SEA (UNCLOS)

The ocean transportation of petroleum by ships has followed the traditional concept of ocean shipping which functions with a high degree of mobility and flexibility based upon free access to the world's oceans. Shipping operates under international law and within the framework of multilateral agreements on seaborne trade. However, with the recognition of marine pollution as a major environmental concern and the desire of coastal states to protect potentially valuable coastal resources, traditional concepts of maritime law, such as freedom of passage or innocent passage, are under modification with implications that effect oil tanker transportation.

A considerable amount of existing international law relates to marine pollution. However, the approaches taken by different countries are not uniform. The approaches adopted by various countries include bilateral, regional and international arrangements. The agreements may be grouped into three major areas: dealing with oil pollution only, regulation of dumping practices at sea generally, and the preservation of the marine environment.[74]

This investigation will focus on the international agreements dealing with vessel source pollution, and the changing maritime concepts as proposed in the Third United Nations Law of the Sea Conference, since these agreements will have a major effect on worldwide oil tanker transportation and pollution requirements.

In order to gain a perspective of the law of the sea and its relationship to vessel source pollution, it is advantageous to briefly review the development of international marine law. Jackson states that "the law of the sea has always been influenced, if not in fact determined by, economical considerations."[75]

Jackson relates that prior to the 1950s, the seabed was not considered of great importance and regulation of the seabed was not a major concern. However, with the recognition of the economic potential of the seabed, coastal states have begun efforts to exercise increased control over the adjacent waters. At least three-fourths of the world's nations possess a coastline, and the current Third United Nations Law of the Sea Conference (UNCLOS III) has become their forum to ensure that they are provided control over the exploitation and protection of the resources within their coastal waters.

The concept of freedom of the sea was asserted in Roman Law, which held that the sea was for the use of all and belonged to the whole of society since it could not be possessed by anyone. Later, states began to exercise sovereignty over areas of the sea. Before the 13th Century, Venice had declared sovereignty over the Adriatic and other Mediterranean, and Scandinavian countries followed similar policies.[76]

Mare Liberum reasserted the doctrine of freedom of the seas when it was written by a jurist, Hugo Grotius, in 1905, to establish the right of the Dutch to trade with the Indies. The Portuguese previously held the exclusive right to trade with the Indies by a Papal Bull in 1493. Again the contention was that since the sea could not be possessed or occupied, it was common to all. Later, in 1635, in an effort to establish the King's sovereignty over British Seas, the Crown had Mare Clausum written to assert their right to control their adjacent waters.[77]

While the concept of freedom of the seas received majority acceptance, actually a compromise was reached. Along with acceptance of freedom of the seas, certain areas adjacent to the coast of a state which could be controlled militarily, were generally recognized to be under that state's sovereignty. However, the extent of the adjacent sea, and the responsibilities and rights of the coastal states were not defined.

The emerging international law of the sea attempts to establish principles defining the extent of the state's responsibilities and right in the territorial seas and adjacent coastal zones. Among the topics under consideration by the United Nations Law of the Sea Conference are the prevention and control of marine pollution, including that caused by ships. IMCO has been the major international entity dealing with standards for marine pollution by ships. Under the present system IMCO established minimum standards and rules applicable to international shipping, and national legislation dealing with domestic shipping. Among parties to the IMCO Convention, national legislation may be equal to, or more restrictive than, international rules. So far, according to Abrahamsson this has not posed a serious problem since potential conflicts between international and national rules have been kept to a minimum by the traditionally accept concepts of innocent passage and limited territorial waters.[78]

The territorial waters of a state have been defined by international law. The United Nations Convention of the Territorial Sea and Contiguous Zone adopted in 1958 and entered into force in 1964, asserted that the sovereignty of a state extends beyond its land territory and its internal waters to a belt of sea adjacent to its coast, defined as territorial sea.[79] The baseline for measuring the extent of the territorial sea is the low water line along the coast. In the case of an irregular coastine, the method of straight baselines was used, joining appropriate points along the coastline. The water on the landward side of the baseline was defined as internal waters of the state. However, in the situation where the straight baselines method enclosed as internal waters those waters which had previously been considered part of the territorial sea or of the high seas, the right of innocent passage was deemed to exist. Under the provisions of the Convention, coastal states may take necessary steps in its territorial sea to prevent passage which is not innocent, or suspend for a period of time, the passage of ships for protection of its security. However, the Convention stipulated that there will be no suspension of innocent passage of foreign ships through the straits which are territorial seas, and are used for international navigation between two parts of the high seas. In the zone of the high seas contiguous to a coastal state's territorial seas, a state may exercise control to prevent infringement of its customs, fiscal, immigration, or sanitary regulations within its territorial sea. The contiguous zone was defined as that area not extending beyond twelve miles from the baseline from which the width of the territorial sea is measured.

A territorial/contiguous zone of twelve nautical miles has become accepted as customary international law at UNCLOS I in 1958. A majority of coastal states have claimed twelve miles or more for their territorial seas. The extent of the territorial seas was specified in the provisions of UNCLOS III, Part II, Article 3:[80]

> Every State has the right to establish the breadth of its territorial sea up to a limit not exceeding 12 nautical miles, measured from baselines determined in accordance with the present Convention.

Larson mentions that if all coastal states extend their territorial seas out to twelve nautical miles, approximately 135 international straits will be overlapped by territorial seas, which may limit freedom of the seas.[81] Included within these international straits are most of the tanker routes such as the Malacca Straits through which tankers transit in the voyage from the Persian Gulf to Japan.

The definition of territorial seas and internal waters is further complicated by archipelagic states. Article 4 of the 1958 Convention of the Territorial Sea and the Contiguous Zone[82] provides for the establishment of baselines of states with a fringe of islands along the coast in its immediate vicinity by joining the outermost points of the islands. This is not specifically applicable to the concept of the ocean archipelago. However, many of the island nations with their separate islands see their territory as composed of areas of water with interspersed islands.[83] The archipelago question was largely ignored in the first and second United Nations Law of the Sea Conferences in 1958 and 1960. With the establishment of a United Nations Seabed Committee in 1970, the island groups have formed a lobby in an attempt to incorporate the archipelago principle into international law. Their approach is to consider the water and islands of the archipelago as a unit by establishing a baseline joining the outermost islands. Some of these claims would include as internal waters, areas which had previously been considered as high seas with freedom of passage by all nations. The Informal Composite Negotiating Text (ICNT) produced at the sixth session of the UNCLOS II in 1977, contained provisions for dealing with archipelagos.[84] Under these provisions, if adopted into international law, certain archipelagic states would be allowed to enclose their islands and intervening waters with a baseline system over which the tate would exercise sovereignty with limitations related to fishing and access rights of neighboring states, and most importantly, the freedom of passage of ships of all states to an "archipelagic sea lanes passage."[85]

The inclusion of island states as "archipelagic states" with the sovereignty rights mentioned above, are under debate and include such factors as geography, history, economic dependency, national security, and concern for the environment. However, the most recent rationale for the island states in claiming sovereignty, is the concern about pollution. The incidence of tanker casualties and the leaking of hazardous cargo, have increased the states' concern for control of navigation through archipelagic waters. The coral islands and reefs of many archipelagic states are particularly sensitive to pollution. Presently, according to provisions in the 1976 and 1977 negotiating texts, ships in transit are to comply with generally accepted international regulations, procedures, and practices concerning pollution.

Another recent trend has been the establishment of an exclusive economic zone extending beyond the limits of the territorial/contiguous zone under coastal state jurisdiction. This move to include within the coastal states' jurisdiction, the adjacent waters which have heretofore been considered the domain of the high seas, contains implications for freedom of the sea. The development of the concept of an exclusive economic zone received its major impetus from the Presidential Proclamations Nos 2667 and 2668, of President Truman in September 1945.[86] These proclamations extend United States jurisdiction over the continental shelf beyond territorial waters for sea and oil exploration (2667), and fisheries conservation (2668). As a result of this United States action, other nations have extended their jurisdiction to cover the continental shelf, if they have one, or two hundred nautical miles from their coastlines, if they do not.[87] The worldwide acceptance of this principle lead to the incorporation of an Exclusive Economic Zone (EEZ) in the UNCLOS ICNT. The adoption of a two hundred mile EEZ had the net effect of reducing the area of the high seas by an estimated 36%.[88]

Within the EEZ, the coastal state has sovereign control which, in addition to control of resource exploration and exploitation, includes jurisdiction for protection of its national interest. This implies, on the basis of national security, the ability to exclude foreign vessels--including the environmentally dangerous oil tankers.

Amendments to the ICNT in 1978 expanded and clarified coastal states' jurisdiction and rights in regard to innocent passage in territorial seas and within their economic zone. In the case of a pollution incident, the flag state, by amendment of Article 221, is required to notify the coastal state affected. The coastal state has the [illegible] board and inspect a foreign vessel in the economic [illegible] suspected violation of international rules and standards has resulted in a "substantial discharge causing or threatening significant pollution."[89]

If there is sufficient evidence to indicate that a ship is in violation "resulting in discharge casuing major damage or threat of major damage" to the coast, territorial seas or economic zone, the coastal state may detain and institute proceedings against the ship, under the amendments to Article 221.[90]

The normal operations of oil tankers in international trade could be affected by provisions ultimately adopted in UNCLOS III. The rights of a coastal state, in the interest of pollution prevention, to restrict passage or impose regulations exceeding those of IMCO could have serious consequences for oil tanker design, construction, and operation.

2.5 LIABILITY ORGANIZATIONS

The implementation of pollution prevention regulations for oil tankers provide a methodology for reducing the potential for oil spills. However, it would be unrealistic to assume that oil spills from tankers will not occur. Increased tanker size and the associated oil spill costs have generated compensation schemes for clean-up, and third party damages resulting from the spills. It is not the intent, nor the objective of this investigation to examine liability organizations in detail, except insofar as they may effect tanker design, construction and operation.

Prior to the Torrey Canyon incident in 1967, adequate national or international arrangements did not exist to compensate oil pollution victims, or to enable governments to recover clean-up costs.[91] As a result of the Torrey Canyon incident, several major compensation schemes came into existence and have been upgraded in the intervening time.

The major compensation schemes consist of two interim voluntary agreements and two international agreements convened by IMCO.

Tanker Owners Voluntary Agreement Concerning Liability for Oil Pollution (TOVALOP) is a tanker owners agreement instituted in 1969 and amended in 1978.[92] Each ship owner is obliged to compensate private individuals and governments which sustain damages due to an oil spill incident, This agreement provides compensation for oil spills occurring in the territorial seas or on the territory of the state. The maximum liability per incident for TOVALOP is limited to the lesser of $147 per gross registered ton (grt) or $16.8 million.

Contract Regarding an Interim Supplement to Tanker Liability for Oil Pollution (CRISTAL) is a cargo owner contract to provide supplemental compensation for tanker owners clean-up costs and third party damage after other remedies have been exhausted. The member oil companies each contribute to a fund based upon each company's annual oil movement and transers. CRISTAL, like TOVALOP, restricts oil pollution damage compensation to pollution incidents in the territorial sea, or on the territory of any state. The liability of CRISTAL is limited to $36 million per incident.

Both TOVALOP and CRISTAL supplement the existing international agreements, the Civilian Liability for Oil Pollution Damage (CLC) and the Fund Compensation, and are due to terminate in 1981.

The international compensation schemes consist of two IMCO conventions, the International Convention on CLC, and the International Fund for Compensation for Oil Pollution Damage (Fund Convention).

The CLC was adopted in 1969 and came into force in June 1975.[93] The CLC established liability for oil pollution damage on territorial seas and on the territory of a contracting state. It requires the owner of a ship flying the flag of a contracting party to establish evidence of financial responsibility to the limit of liability, the lesser of $147 per grt or $16.8 million. After a pollution incident the ship owner is required to set up a fund to the liability limit, for the purpose of compensating damaged parties.

The most recent international convention was the Fund Convention which came into force on October 16, 1975. The Convention provides compensation to the extent that the CLC is inadequate, and relieves the ship owners from a portion of the financial burden imposed by CLC. Compensation is limited to $36 million for damaged parties and to shipowners, for damages in excess of $10 million, but less than $36 million. Contracting states contribute to the Fund in relation to their annual amount of imported oil. The Fund is to be maintained at $36 million, or, if that proves inadequate, increased to $72 million.

The Fund can defend itself from liability under certain conditions. In the case of shipowners claiming indemnity under the liability limitations of CLC, the Fund can defend itself by showing that the incident was caused wholly or partially by failure to comply with (among others) the International Convention for the Prevention of Pollution of the Sea by Oil, 1954, as amended in 1962.[94]

This provides an incentive for shipowners to adhere to the 1954 Convention which contains provisions related to the operation of oil tankers. Consequently, shipowners and cargo owners have a vested interest in improving oil tanker performance and safety through improvement in design, construction, and operation.

3. SONAR OIL THICKNESS SENSOR

3.1 DESCRIPTION

The Sonar Oil Thickness Sensor-Tanker (SOTS-T) system was adapted from the basic SOTS unit designed and developed by Sternberger to measure the thickness of oil spills on the sea surface.[95] A detailed description of the SOTS' design is not within the scope nor objective of this investigation. Reference may be made directly to Sternberger's work for additional details. A description of the basic operating concepts, however, is presented here as fundamental to the understanding of the development of the SOTS-T system.

The SOTS unit is an inverted echo sounder (fathometer), which measures the time delay between two acoustic echos. The echo sounding transceiver is located in the water medium, and transmits acoustical signals to the oil layer above. The time delay is measured between the first echo received from the bottom of the oil layer, and the second echo received from the top, at the oil/air interface.

In flat, calm conditions, with stationary boundaries, determination of oil thickness would be a simple time measurement on an oscilloscope. However, the surface of the sea is not stationary, but consists of waves which reflect the transmitted signals in many directions, as the wave slope changes. Consequently, most of the echos from the interfaces would be lost or inadequately returned, thus limiting thickness measurement. The SOTS overcomes this limitation by utilizing a microprocessor which is able to collect, retain, and operate on data from the echos that do return to the transceiver during the periods of zero wave slope, which occur regardless of how active the wave surface may be.

The microprocessor controls the echo sounder, times the echo intervals, compensates for large fluctuations in echo levels, averages successive pulses, and statistically determines oil layer thickness, which may be presented in digital form.

The functional design concepts of the SOTS are shown in Figure 3.1.1.[96] The microprocessor controls the entire device, as depicted by the dashed lines. The analog to digital (A/D) conversion and time gating is standard procedure for converting analog signals into the digital form required by computers. Software controls the operation of the microprocessor, thus the SOTS device. The software also provides for bad data detection, data archiving, and determination of statistical parameters.

The remote sensing and detection are performed by the inverted echo sounding SONAR transceiver. An illustration of an oscilloscope photograph of an acoustic return

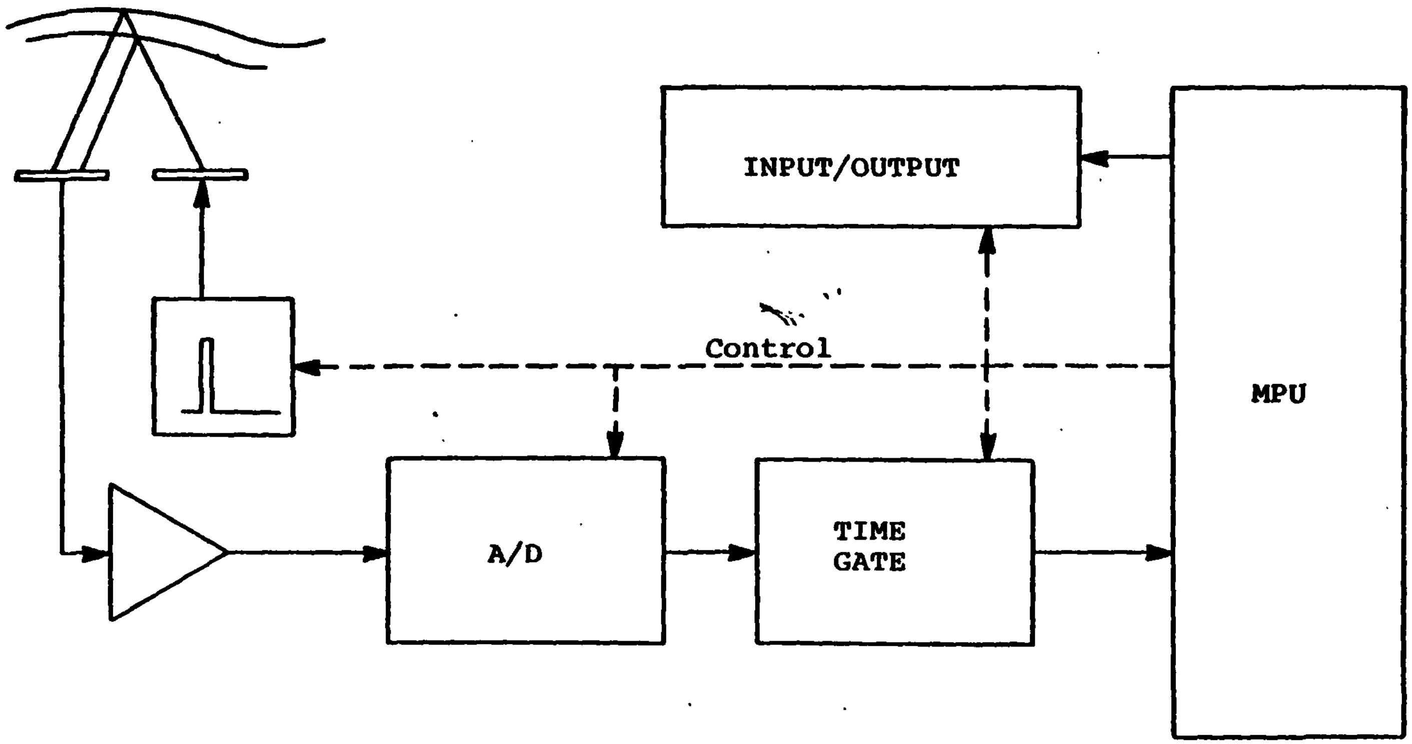


FIGURE 3.1.1 SOTS Function Design Concept.

from an oil layer on water is shown in Figure 3.1.2.[97] The first wave packet, at the left side of the trace, is the return corresponding to the water/oil interfaces; and, the larger second wave packet corresponds to the return from the oil/air interface. The wave packet to the far right was an unwanted echo, internal to the transducer, and was accounted for in the SOTS analysis. The large impedance difference between oil and air produces the larger second return. The acoustical impedance of water and oil are much closer and result in the smaller, first return. The water/oil return, though smaller, is not masked by the second larger return since it always occurs first.

The SOTS device does not need to perform extensive data analysis on the exact acoustic waveform. Rather it need only detect an envelope of data corresponding to the return from the interfaces. The processing is further reduced by a determination of whether the amplified received signal exceed a preset threshold or not. This is advantageous for data detection, and leads to direct voltage level comparison with a reduced volume of generated data.

Time gating is used to provide a time window for the collection of data of interest. The time gating is peformed by selectively starting a clock via the synchronized pulse, and stopping it after a predetermined time interval. The time gating allows the oil/air return to be set about two-thirds of the way into the window, and

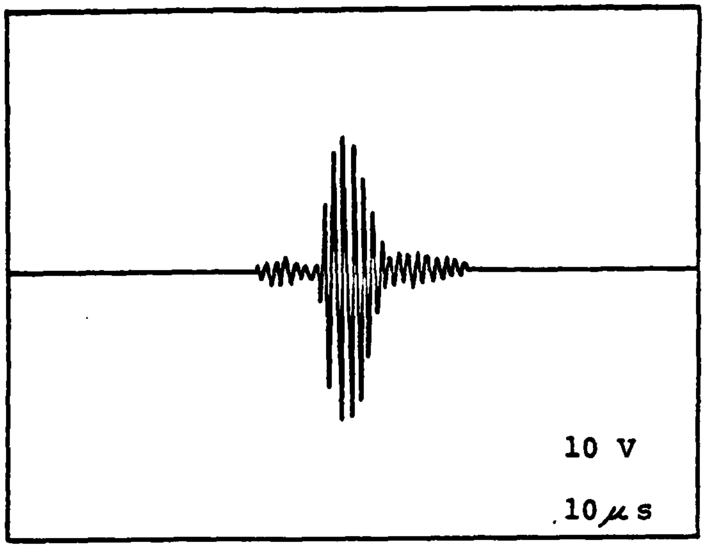


FIGURE 3.1.2 Return Acoustic Siganl From an Undisturbed Oil-on-Water Layer in a Laboratory Test Tank.

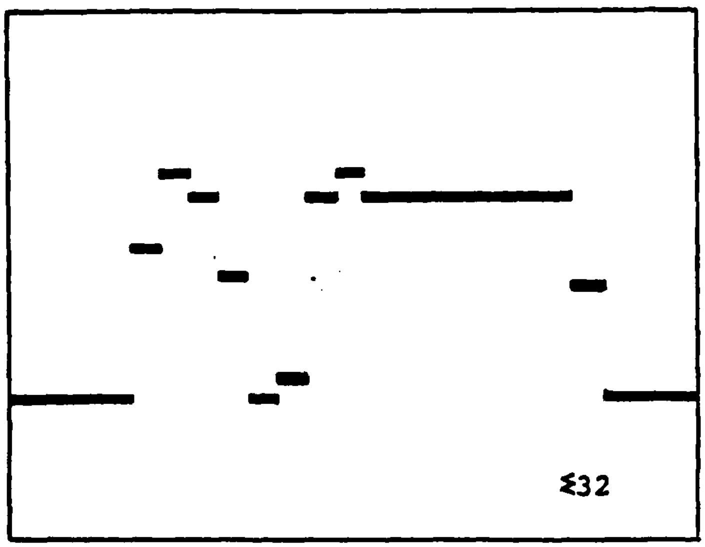


FIGURE 3.1.3 Calm Surface Memory Map of 32 Successive Acoustic Pulses, Summed Together for Processing Gain. The Two Highest Value Bins Indicate the Computed Centroid Locations.

insures that there is sufficient time prior to the oil/air return in which to detect the water/oil return.

The SOTS analysis technique locates the interfaces by determining the centroids of the sampled data which corresponds to the interfaces. The oil/air interface is first found by locating the centroid of all of the sampled data. Next, the water/oil interface is located by finding the centroid of the truncated portion of the sample points at a given distance below the main oil/air centroid. Since the acoustical return from the oil/air interfaces is so much larger than the water/oil return, the centroid of the entire sample accurately locates the oil/air interface. Figure 3.1.3 shows a calm surface memory map of 32 successive acoustic pulses, with the two highest values indicating the centroid locations.[98]

The SOTS unit uses a 1.0 MHz carrier frequency which provides the required resolution, and allows for a directive transducer that is a convenient size. The resolution is 0.75 mm of oil layer thickness. The speed of sound in oil, although different than water, is not a major consideration since the available published information on sound velocity of a limited number of oils is within 10% of that of water. More importantly, the oil layer under consideration is thin, thus the error in sound velocity is negligible. However, as discussed later, the sound velocity of crude oil is a critical parameter in the SOTS-T, since the depth of oil in a cargo tanker can exceed 100 feet.

Attenuation was examined by Sternberger since high frequency acoustic signals are subject to high attenuation with distance. Attenuation coupled with the directivity pattern, influenced the positioning of the SOTS transducer (relative to the surface) when deployed for measuring oil spills. To provide an adequate sonified area on the sea surface, and for optimum signal return under wave conditions, the SOTS unit uses a 6° beam width (½ power total angle) with transducer, at a frequency to 1.0 MHz.

The SOTS data is processed in real time without interaction from an operator. The operator input was eliminated by use of software that is programmed to respond to anticipated conditions. The SOTS device can continuously sample to track changes in oil layer thickness, or, in another operational mode, measure the average value and variance of the thickness of an oil layer on an intermittent sampling basis.

Laboratory testing conducted by Sternberger verified the operational accuracy of the SOTS unit. Even in the extreme case of oil weathered for two months, with an acquired thick organic growth which reduced the oil/water reflection coefficient by nearly 70%, the SOTS device measured oil thickness within 5% of the actual value.

3.2 APPLICATION TO OIL TANKERS

The basic SOTS operating methodology is the detection and measurement of the two interfaces of a thin layer of oil. The adaptation of the SOTS unit to oil tankers required the measurement of a much larger separation of interfaces which would occur in vessel cargo tanks.

The SOTS-T measurement system, for use in oil tankers, required the capability to monitor liquid in a variety of situations: cargo levels, stripping, slop tank interface locations, departure ballast oil layer thickness, and dedicated ballast level.

The cargo level measurement case is shown in Figure 3.2.1 In this case, the apparatus would be required to measure the various liquid levels throughout the normal loading, transit, and unloading operations.

During the loading operation, the SOTS-T system would be required to track and measure a single oil/air interface. During a long voyage, such as from the Persian Gulf to the United States, water settles out of crude oil and/or collects from other ship-related sources, and accumulates in the bottom of the cargo tanks. The location of the resultant water/oil interface must be determined, for custody transfer measurement, prior to unloading.

Unloading measurement requirements depend upon the method of tank cleaning to be used. If the tanker is equipped with the Crude Oil Washing (COW) method for tank cleaning, a stripping monitor would be required by IMCO

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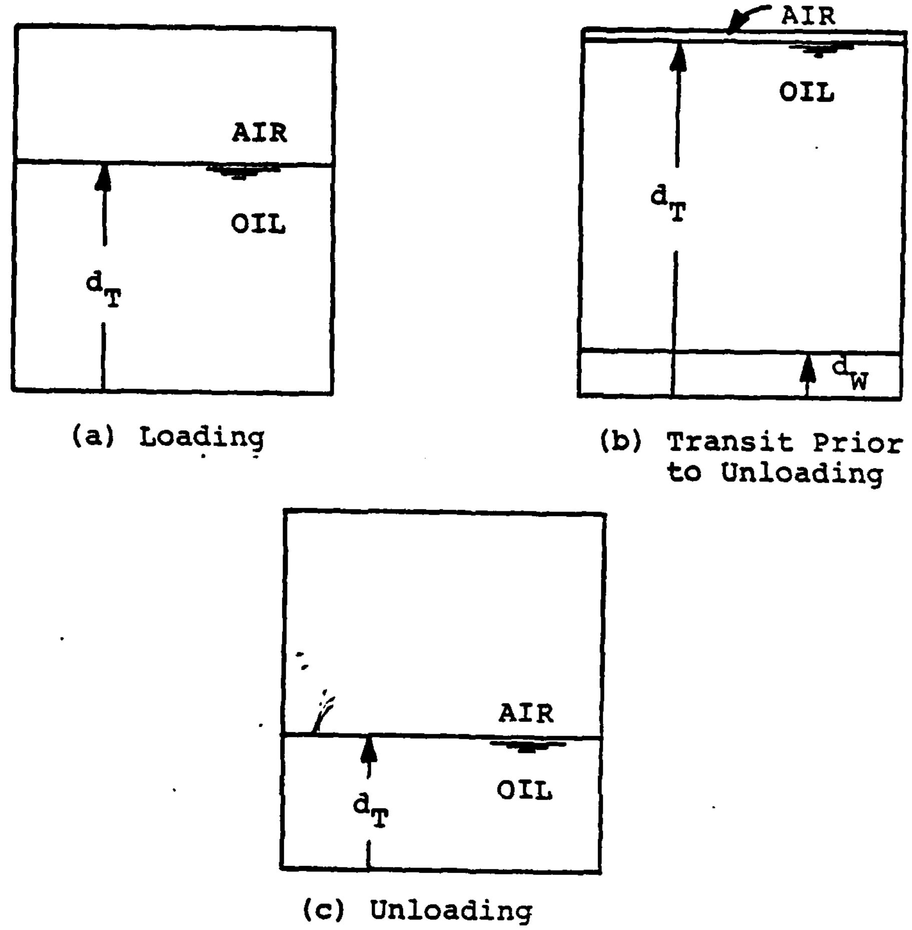


FIGURE 3.2.1 Cargo Measurement: (a) Loading (b) Transit Prior to Unloading (c) Unloading

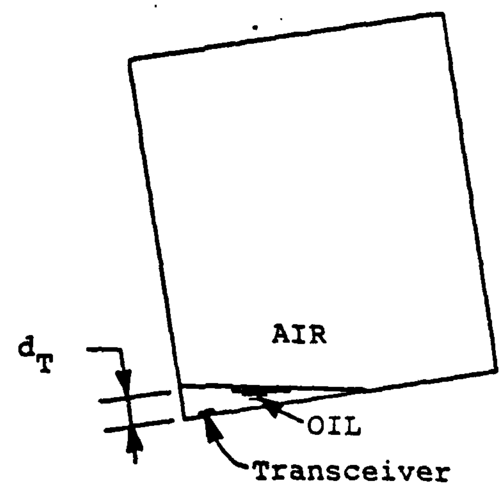


FIGURE 3.2.2 Stripping Monitor

to verify that the tank is "dry" after stripping. The stripping suction located near the bottom of the tank collects the washings which are then pumped ashore by the stripping pumps. A tanker with the free flow system would normally develop trim by the stern as the wedge of oil is pumped out, starting with the aft tanks and progressing toward the bow. The tanks are cleaned by starting at the bow and cleaning tanks toward the aft, as unloading progresses.

The SOTS-T measurement system would be located near the aft portion of a tank, and would measure the small wedge of oil remaining after the stripping pumps had removed the cargo and washings. This situation is shown in Figure 3.2.2. The IMCO regulations for a stripping monitor, as mentioned in Section 2.1, define dry as a "small quantity of oil near the stripping suction with the tank dry everywhere else." The measurement of this wedge would consist of determining the distance to a single oil/air interface.

Since the tanker develops trim by the stern during loading and unloading, operations of the SOTS-T system would be required to have a trim correction. This correction would be accomplished by a simple mathematical computation related to the geometry of each tank.

The slop tank, as shown in Figure 3.2.3, receives oily wastes from normal tanker operations and, in the case of tank cleaning with water, receives washings containing water, oil, and tank residues. The water and oil are

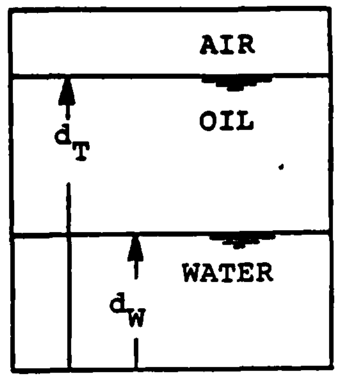


FIGURE 3.2.3 Slop Tank Measurement.

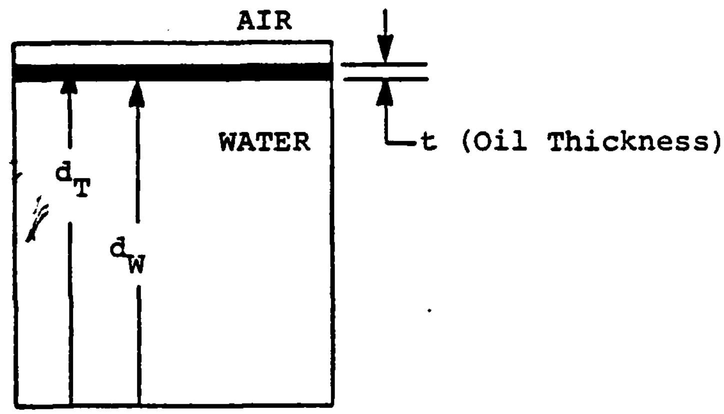


FIGURE 3.2.4 Departure Ballast Measurement.

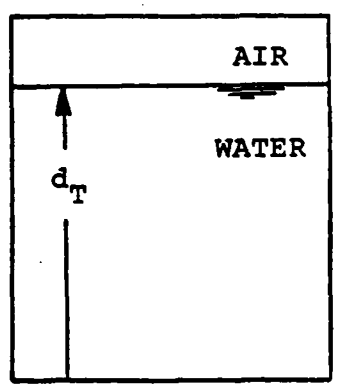


FIGURE 3.2.5 Segregated Ballast Measurement.

allowed to separate by gravity, resulting in the oil floating above the water. IMCO regulations require a water/oil interface detection device to monitor water/oil interface location for accurate control of the decanting operation. In this situation the SOTS-T system would be required to measure both the oil/air and water/oil interface. The interfaces would be variable and the SOTS-T system would be required to track the interfaces during the variations in the slop tank level. The slop tank may be a special tank reserved for this purpose or may be one of the cargo tanks used temporarily for containing slops. Consequently, the measurement sequence for the slop tank would be required to be interchangeable with cargo tanks.

IMCO has established the maximum amount of oil permitted in a departure ballast tank which previously had been used for cargo and subsequently cleaned by the COW method. The ratio of the volume of oil floating on top of the ballast to the volume of the tank is not to exceed 0.00085. This situation is shown in Figure 3.2.4. As an example, a large tank of 30 meters depth by 15 meters square would be allowed a maximum oil layer thickness of 26 mm. In this situation the SOTS-T unit would be required to detect and measure this thin oil layer thickness at a considerable distance, a maximum of about 30 meters, from the bottom of the tank.

The final measurement situation would be for an oil tanker fitted with segregated ballast tanks. This situation is shown in Figure 3.2.5, and consists of detecting and measuring a single water/air interface at any tank depth.

In response to the variety of oil tanker measurement conditions discussed, the SOTS-T unit would be required to detect an interface at any height within a tank and measure either a single interface or both interfaces with the sampling window.

The SOTS-T unit would be programmed, in general, to track the sampling window up from the transceiver until an interface was detected, and to locate a single interface within the window. In the cases where a thin thickness of oil occurs, the program would enable the basic SOTS dual interface detection routine. The tracking of the sampling window would be accomplished by a sequence of overlapping sampling windows, each of which would correspond to the basic SOTS 256 bit sliding sample window. The program would search for a wave packet within the window from which to compute a centroid. If a centroid was not computed in a window because of a lack of acoustic return, the program would advance to the next window position in time. In this manner, the SOTS-T unit would search for an interface starting at the surface of the transceiver and progressing vertically until an interface was detected.

The specific logic used by the SOTS-T unit for each of the tanker's measurement situations is described in detail in Section 5, Cargo Management System.

The two major characteristics of the SOTS-T system to be considered for adaptation to oil tankers consisted of resolution accuracy and energy output as limited by intrinsic safety requirements. Acoustic accuracy is required for compliance with custody transfer standards. Energy output as represented by a signal level (SL) at the transceiver dictates allowable transmission loss in the form of spherical spreading and absorption.

The acoustic accuracy is largely a function of acoustic carrier frequency. The desired resolution is equal to one-half of the wave length for two-way travel. The desired frequency is determined from the well known relationship that $f\lambda=c$. However, the selection of trans-frequency also affects attenuation of the acoustic signal due to absorption. As frequency increases, the attenuation of the signal by absorption increases. Consequently, a design compromise must be made between high frequency for acoustic accuracy, and lower frequency for less attenuation due to absorption. The basic SOTS frequency of 1.0 MHz was suspected to yield unacceptable attenuation. As a result, for analysis purposes, a transducer frequency of 200 kHz was initially selected.

A 200 kHz frequency has a one-half wavelength of 3.75 millimeters. The current best accuracy experienced by Exxon in measuring liquid level for custody transfer using the hand tape was about 1/8 of an inch, which corresponds to 3.2 millimers. Therefore, a SOTS-T system operating at a frequency of 200 kHz would be within the acceptable range for optimum custody transfer accuracy.

The energy output of the SOTS-T unit was required to be within allowable intrinsic safety limits. The SOTS-T electronics and power supply would be located in a non-hazardous location such as the cargo control room. The only elements in a hazardous location would be the cabling and transceivers receiving the output signal. As a result, only the energy output of the unit as influenced by the worst case of fault condition within the circuit was required for intrinsic safety analysis.

The National Fire Protection Association 493 Standard[99] was used to evaluate intrinsic safety of the SOTS-T unit. It was augmented by the Underwriters Laboratory U1913 Standard,[100] since both publications are similar and utilize the same graphs for relationships between electrical parameters and minimum ignition currents for evaluation by the comparison procedure.

The basic SOTS unit used a 100 volt input to a voltage tripler of three capacitors with a total of 1300 picofarads to provide 300 volts for the acoustic pulse. This corresponds to a peak power of 103 watts. Utilizing the comparison procedure and Figure 5-1.5(a) of NFPA 493 for capacitance circuits, a capacitance of 1300 picofarads was found to fall below the graph. The allowable voltage corresponding to the extrapolated curve was well above the 300 volts used in the basic SOTS unit. However, in

TABLE 3.2.1

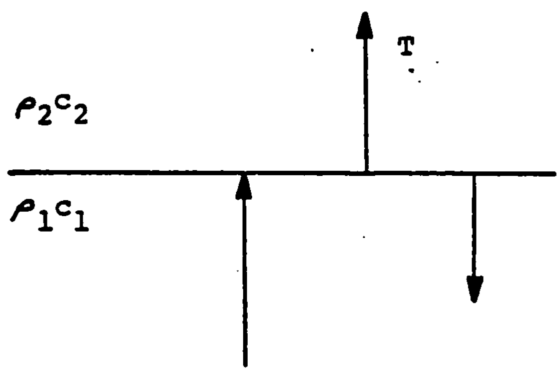
SONAR Parameters

Parameter	Value (db//μbar)	Source
NL	-55.0	Environmental
Ns	69.0	Hardware
DI	29.0	Hardware
TS	-16.5	Environmental

TABLE 3.2.2

Fluid Characteristics

Medium	c (m/s)	ρ(kg/m^3)	c (kg/m^{2}s)
Water	1500	1000.0	1.5×10^6
Olive Oil	1400	900.0	1.3×10^6
Lube Oil	1450	800.0	1.1×10^6
Air	330	1.3	430



$$R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}$$

FIGURE 3.2.6 Rayleigh Reflection Equation conversation with a classification society on the interpretation of the graph, it was decided that since the capacitance was below the curve, the conservative approach would be to reduce the output voltage. Consequently, a voltage of 150 Vpp was used for the acoustic pulses, resulting in a peak power of 26 watts for the SOTS-T configuration.

The SONAR equations were used to predict acoustical performance and determine allowable transmission loss for design of the SOTS-T configuration. These equations take into account hardwared and environmental constraints.[101] Table 3.2.1 is a partial list of SONAR parameters applicable to the SOTS-T hardware and environmental conditions.

The parameters, with the exception of the ambient noise level (NL) have been calculated based upon actual SOTS hardware measurements made by Sternberger. The ambient noise level was determined to be -68 db from an empirical curve,[102] for the open ocean. It was recognized that the transceivers would be located inside of the ship within various tanks and would be subjected primarily to ship related noise. The literature[103] indicates that ship noise occurs in the decade from 50 to 500 Hz, well below a SOTS-T operating frequency of 200 kHz.

Using an ambient noise level of -68 db for analysis purposes, the amplifier self noise (NS) was 137 db higher than NL and the limiting noise factor. This was also the case with the basic SOTS unit. Consequently, the SOTS-T unit was considered to operate in a self noise limited mode. The transducer directivity (DI) is a function of the frequency and size of the transducer crystal. The DI parameter was obtained from a standard monograph.

The target strength (TS) was derived for both the water/oil and the oil/air interface. Table 3.2.2 lists the fluid characteristics of water and several varieties of oil. Water and oil are the closest in specific acoustic impedance, and produce a much lower reflection coefficient than at the oil/air interface. The reflection was determined using the Rayleigh reflection coefficient shown in Figure 3.2.6. The reflection coefficient, R, for the oil/air interface approaches -1.0. The R value for the water/oil interface was $0 < R << -1$. The negative sign indicates a phase reversal of the signal upon reflection from the interface.

The slop tank may also contain an emulsion at the water/oil boundary which could affect interface detection, hence, target strength. S.A. Berridge,[104] in a study of oil spill characteristics suggested that tank cleaning with water directed under high pressure could produce emulsions composed of 30% water. The presence of an emulsion would reduce the reflectivity at the water/oil interface. In tests by Sternberger, a 70% reduction in interface reflectivity caused by organic growth did not appreciably decrease the interface detection capability of the SOTS unit. The SOTS sampling procedure, and the larger sonified area of the SOTS-S system would both act to enhance interface detection in the presence of emulsions.

The ocean environment contains sources other than the well defined oil/air and water/oil boundary for the interception and reradiation of the acoustic source energy. The condition is termed reverberation level (RL). The RL is composed of two parts: volume and boundary reverberations. As discussed by Sternberger, because of the received signal time gating in the basic SOTS unit, volume reverberation was the only contributor.

The source of volume reverberation in the ocean has been identified as biological. Since the SOTS-T unit would operate, in the most severe cases, entirely in an oil medium, ocean volume reverberation as used in the SONAR equations would not be applicable. Laboratory testing for attenuation would include the effect, if any, of volume reverberation in oil. Consequently, the SOTS-T unit was considered to not be limited by reverberation level. This was also the case with the basic SOTS unit.

In calculating the allowable transmission loss for system design, the detection threshold was considered to be 10 db. The data detection method of the SOTS unit required only a few db of signal above noise for processing. Consequently, a conservative value of 10 db was assigned for acceptable detection threshold.

The allowable transmission loss for the SOTS-T system depends upon attenuation in the medium and the target strength of the interface. The measurement of an oil/air interface would involve the transmission of a signal through an oil medium, which would have appreciable attenuation due to absorption, and reflection from an interface with a maximum reflectivity characteristic. The measurement of a water/oil interface, on the other hand, would involve the transmission of a signal through water, which has a low attenuation due to absorption, and reflection from an interface with reduced reflectivity characteristics.

The allowable transmission loss of a SOTS-T transceiver corresponding to an oil/air interface situation, the worst case, was calculated to be 65 db. For the water/oil situation the allowable transmission loss was calculated to be 48 db.

Laboratory testing was conducted to determine attenuation of a signal due to absorption for use in the SOTS-T configuration.

4. LABORATORY TESTING

4.1 GENERAL PROCEDURES

The general procedure in the laboratory testing was to determine the necessary acoustical properties of petroleum to be incorporated into the SOTS-T configuration. It was found that oil tanker cargo tank conditions could not be simulated in the laboratory due to the physical sizing problem. A typical VLCC of 250,000 dwt has cargo tanks of approximately 120 feet depth, and an 80,000 dwt tanker has cargo tanks of about 60 feet depth. The acoustical beam pattern width produced by the proposed transducer, 200 kHz, required that a large width tank would have been necessary in addition to the depth, to simulate actual cargo tank conditions. Consequently, even a scaled down tank would not have been feasible due to the volumetric requirements of the beam pattern width. The liquid surface within the tank would also be required to be activated in some fashion to produce waves which are present in cargo tanks. Aside from the problem of providing a tank large enough to conduct stationary tests, were the additional problems of acquiring a large amount of crude oil, transportation, variability in crude oil composition, and cleanup operations. Based upon these factors, it became apparent that a stationary tank was not a practical laboratory testing method.

Since tank simulation testing was impractical, the adopted procedure was to investigate, in the laboratory, acoustical parameters necessary for tanker measurement and incorporate them into the SOTS-T configuration. The acoustical properties to be determined were: (1) velocity of sound measurements in crude oil, (2) attenuation characteristics, and (3) selection of proper transducer frequency.

The SOTS device for measuring the thin layer thickness of oil floating on the sea used a transducer frequency of 1.0 MHz. The selection of this frequency was mainly a function of resolution. With the 1.0 MHz frequency, a resolution of 0.75 mm in layers greater than 3.0 mm, was obtained by Sternberger. Frequency in the tanker application became important due to the attenuation of the signal by absorption, as it traveled through the much greater height of oil in a cargo tank. Attenuation by absorption is a function of frequency, and as the frequency increases the signal loss increases. To reduce absorption losses, the selection of a lower frequency was deemed advantageous. In addition, the 1.0 MHz transducer possessed a narrow beam pattern, on the order of 5-6°. This high directivity would necessitate precise alignment to obtain valid oil depth measurement over large depths. Consequently, in view of the restrictions of the 1.0 MHz transducer for potential tanker use, a 200 kHz frequency transducer was selected. This transducer was of lower frequency to reduce attenuation due to absorption, and the beam pattern was broader, about 16°, which would help compensate for installation misalignment. The 200 kHz transducer was readily available without any special fabrication.

There is a lack of information in the literature about the velocity of sound in crude oil and petroleum products. Gold and Ogle[105] examined methods for estimating sound velocity in liquids, including organic compounds. Of the various formulas for the speed of sound which they examined, they recommended the method given by Rao:

$$v = 0.032808\left(\frac{\beta \rho}{M}\right)^3 \qquad (4.1)$$

where the speed of sound, v, is related to density, ρ, the molecular weight, M, and β is a constant determined by the sum of structural constants which are associated with the basic organic structures and hydrocarbon radicals contained in the liquid.

Their accuracy calculations show about 4.3 ± 24.4 average percent error for polar hydrocarbons. Unfortunately, to determine the sound velocity, the entire structural composition of the subject liquid is required. Crude oil is made up of a large variety of hydrocarbon elements and is not analyzed in this detailed fashion prior to transportation. Therefore, this calculation method was not practical.

L.C. Jones, chairman of the American Petroleum Institute (API) Committee on Marine Accountability (COMA). The body concerned with cargo measurement, stated that "we do not know of any data on velocity of sound in crude oil."[106] However, Jones defines the problem of relating sound velocity and API parameters by beginning with the basic principle of sound velocity, where the sound velocity, v, is calculated from the bulk modulus, E, and the density, ρ:

$$v = \sqrt{\frac{E}{\rho}} \tag{4.2}$$

Since crude oil density is measured by the oil industry in terms of API Degree Gravity at 60°F instead of conventional density units, the following relationship between API gravity and specific gravity, which is related to density, is given:

$$\text{API Gravity} = \frac{141.5}{\text{Specific Gravity at } 60^{\circ}\text{F}} - 131.5 \tag{4.3}$$

From this relationship it can be seen that API gravity is inversely proportional to specific gravity, thus density. As indicated above, API gravity is given in degrees at a standard temperature of 60°F.

To calculate the velocity of sound from equation (4.1) and given the density or equivalent API gravity, the bulk modulus can be estimated from a correlation of the API gravity at 60°F, and compressibility as given in API

Standard 1101, "Measurement of Petroleum Liquid Hydrocarbons by Positive Displacement Meter."

For comparison purposes the sound velocity of kerosene, which was known, was calculated from API parameters by determining the API gravity corresponding to the density in kerosene, the bulk modulus from API tables and substituting these values into equation (4.2). Jones provided the following comparison and it is reproduced here to illustrate the difficulty of calculating the velocity of sound from the normal API parameters and other variations particular to oil tankers.

From the Handbook of Chemistry and Physics,[107] a kerosene with density = 0.81 g/cc at 25°C (ρ = 810 kg/m^3) the velocity of sound was v = 1324 m/sec at 25°C and the change of velocity of sound with temperature was $\Delta v/\Delta T$ = -3.6 m/sec at 25°C. From API tables relating API gravity to density and the volume reduction factor to 60°F from 25°C (77°F), the API gravity for an oil corresponding to a density = 0.81 g/cc at 25°C was equivalent to 41.8° API gavity at 60°F.

An estimate of the bulk modulus was determined for an oil of 41.8°F API gravity using the correlations of API Standard 1101 which relates API gravity, temperature, and compressibility factor, F, which is expressed in percent per 1000 psi. For a 41.8° API gravity at 77°F (25°C), the compressibility factor was 0.59%.

According to the API equation utilizing the Standard

1101, the bulk modulus is:

$$E = \frac{\text{pressure}}{F} \quad \text{where } F = \text{compressibility factor} \qquad (4.4)$$

substituting the appropriate values and conversion factors:

$$E = \frac{1000}{0.0059}\left(\frac{\text{lb-force}}{\text{in}^2}\right) x \ \frac{1}{2.2}\left(\frac{\text{kg}}{\text{lb}}\right) x \left(\frac{1}{0.0254}\right)^2\left(\frac{\text{in}}{\text{m}}\right)^2 x \ 9.8\left(\frac{\text{m}}{\text{s}^2}\right)\left(\frac{\text{kg-mass}}{\text{kg-force}}\right)$$

therefore, $E = 1.17 \times 10^9$ kg(mass)/msec.

Calculating the velocity of sound, the oil at 77°F (25°C) is:

$$v = \sqrt{\frac{E}{\rho}} \neq 1202 \text{ m/sec}$$

The error in the calculated value from the tabulated value is:

$$\text{Error} = \frac{1324 - 1202}{1324} = 0.092 \text{ m/sec} = -9.2\% .$$

The error probably results from uncertainty in the calculation of bulk modulus since compressibility and molecular structure may be related in a more complex manner than that suggested by the API graph relating API gravity and percent compressibility. The importance of molecular structure on sound velocity in hydrocarbons was similarly reflected in the use of Rao's equation described previously. The commonly available crude oils vary in API gravity from approximately 10-50° which indicates a broad range in density and bulk modulus, hence, sound velocity. Due to the inherent inaccuracy in determining sound velocity of crude oil from API data, the calculation of sound velocities would be useful only in estimating a range of velocities to be encountered.

Temperature effects on the velocity of sound are another important variable. Jones also investigated this aspect in relating the change of bulk modulus and density with temperature changes.

Referring again the basic sound velocity equation (4.2), with regard to temperature:

$$v_t = \sqrt{\frac{E_t}{\rho_t}} \qquad (4.5)$$

where v_t = velocity of sound at temperature, t

E_t = bulk modulus at temperature, t

ρ_t = density at temperature, t.

Differentiation of equation (4.5) with respect to temperature:

$$\frac{dv}{dT} = \frac{1}{2\rho_t{}^2} \sqrt{\frac{\rho t}{E_t}} \left(\rho_t \frac{dE}{dT} - E_t \frac{d\rho}{dT}\right).$$

Next, the change in velocity with temperature for the 41.8° API gravity oil corresponding to kerosene at 77°F (25°C) was calculated.

The change in density with temperature calculated by use of API Table 6, "Volume Reduction to 60°F," and API Table 3, "API Gravity to Specific Gravity and to Density:"

$$\frac{d\rho}{dT} = \frac{810 - 810/0.9917}{10^{o}C} = \frac{810 - 816}{10^{o}C} = -0.68 \frac{kg}{^{o}C}.$$

The change in bulk modulus with temperature, dE/dT, was obtained from a curve relating percent compressibility and temperature. The slope of the tangent to the curve at 77°F (25°C), dE/dT, was approximately 0.0028% per °F x 1000 psia at the compressibility factor, F, of 0.59%, which corresponds to the 41.8° API gravity oil at 77°F.

The percent change in compressibility per °C is:

$$\frac{100 \times 0.0028}{0.58} \times \frac{1.8^{o}F}{^{o}C} = 0.087 \frac{\%}{^{o}C}.$$

thus

$$\frac{dE}{dT} = -8.087 \times 1.17x10^{9} = -1.02x10^{7} \ \frac{kg(mass)}{in\ sec^{2}\ ^{o}C}$$

$$\frac{dv}{dT} = \frac{1}{2(810)^{2}}\sqrt{\frac{810}{1.17x10^{9}}}\left[810(-1.02x10^{7}) - 1.17x10^{9}(-0.68)\right]$$

$$= -4.73 \text{ m/sec/}^{o}C \text{ at } 25^{o}C.$$

The error in calculated change in sound velocity with temperature compared with the given value was:

Tabulated value: $\Delta v/\Delta T$ = -3.6 m/sec at 25°C

$$\text{Error} = \frac{-4.73 - (-3.6)}{3.6} = -30\%.$$

As the above calculation indicates, the effect of temperature on the sound velocity was a very important factor, indicating the need for reliable temperature information.

The temperature of the shipboard cargo ranges from as high as 150°F (immediately after loading) to that of the sea, as heat is transferred from the cargo to the sea during the voyage.

Jones also states that the temperature coefficient of velocity for the sample of kerosene of -3.6 m/sec/$^{\circ}$C corresponds to about 0.3% per $^{\circ}$C, which is much higher than the thermal expansion of the liquid. This means that acoustical gauging will be more sensitive to error in mean average temperature than the conventional measurement of liquid level with the hand held plumb bob and steel tape.

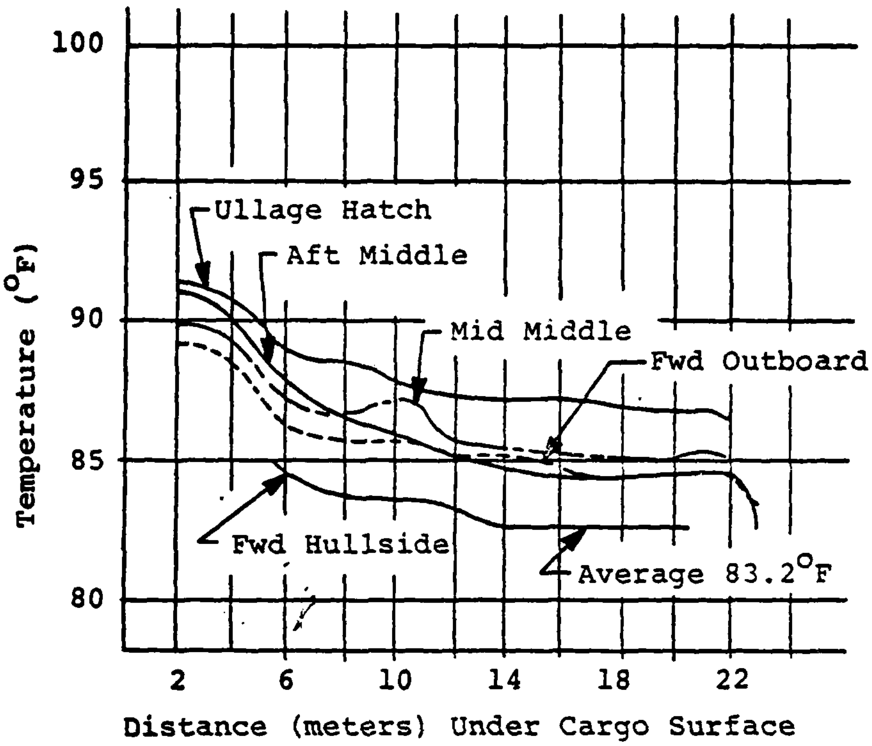
Jones acknowledges that "current measurement of temperature in cargo tanks is a problem" due to vertical and horizontal temperature gradients that result from heat transfer of the cargo to the sea.

A study of the problem of vertical and horizontal temperature gradients in cargo tanks was undertaken by Mobil Oil Corporation, and the results released in their company report dated June 1978.[108] Tests were conducted on board the Mobil Pinnacle during a 13-day voyage in which temperature profiles were taken in various cargo tanks. The most severe gradients appear to occur in the wing tanks which have the most exposed surface to the sea for heat transfer. Figure 4.1.1 is a reproduction from the report, and indicates the extent of the gradients measured. As shown in Figure 4.1.1, depending upon location, the temperature may vary between 92°F at the liquid surface on the inboard bulkhead to approximately 80°F at the bottom of the tank at hullside. Obviously, these gradients are reflective that particular voyage, and a voyage under more extreme sea temperatures may result in larger gradients. However, the implication is clear that temperature gradients do exist and present a problem to the use of acoustic methods for liquid level gauging.

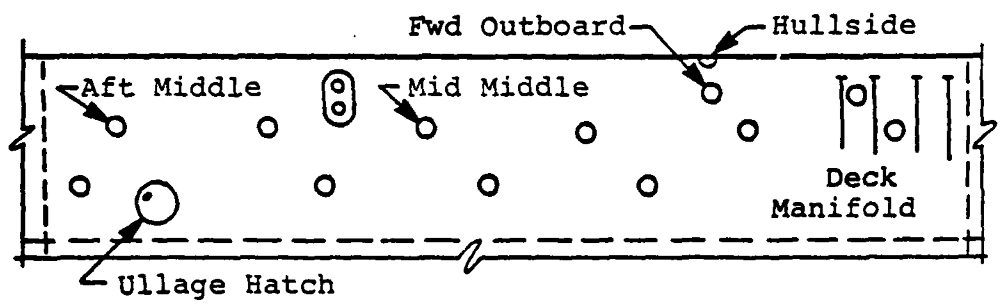
The above analysis indicates that the application of an acoustic sensor must take into account the effect of thermal gradients, both vertical and horizontal, and the variation in the composition of the crude oil as reflected in the change of bulk modulus and density with composition.

The next area of investigation was the measurement in the laboratory of sound velocity and attenuation characteristics of crude oil.

Since crude oil is difficult to obtain and transport without special permits, it was decided to select a petroleum product containing characteristics as near to crude oils as possible, yet available locally. As mentioned previously, crude oil composition and properties vary over a considerable range. Depending upon the source, crude oil



#4 Port Tank



#4 Port Wing Tank - Schematic

FIGURE 4.1.1 Horizontal Wing Tank Temperature Differentials may be what is termed a "light" crude which flows easily, or may be termed a "heavy" crude which has a high viscosity which requires it be heated to be pumped aboard a tanker. With these characteristics in mind, it was determined that a heavy fuel oil would be representative of crude oil, and a #6 fuel oil was selected. It is a heavy viscous refined petroleum product containing the heavier components of crude oil which remain after the lighter fractions have been removed by distillation.

Sound velocity was determined by the use of a velocimeter. The apparatus consisted of a target placed a fixed distance from the transducer which functioned as a transceiver, able to transmit and receive acoustical signals. The reflective target was corprene, a material with air trapped in a cork matrix. This was cemented to an aluminum backing plate and sealed with a thin layer of epoxy. The transducer frequency used for testing was 200 kHz. The velocimeter was calibrated in distilled water, for which the sound velocity was known. The exact distance of the target from the transducer was determined from the time required for the travel of the acoustic signal from the transducer to the target and back. An approximate travel time was determined by observing the output pulse and return echo on an oscilloscope. A more accurate determination of travel time was obtained by a frequency counter which counted in microseconds.

The distilled water and the #6 fuel oil were placed in containers which held about thirty gallons of liquid each. The two liquids were allowed to reach the same ambient temperature, and the velocimeter was then calibrated in the distilled water. To determine the sound velocity in the #6 fuel oil, the velocimeter was immersed in the fuel oil and the time of travel recorded. The sound velocity was then calculated from the measured travel time and the known distance of travel.

The sound velocity of distilled water at 19°C was calculated to be 1470.5 m/sec by standard equations in the literature. The sound velocity in the #6 fuel oil was measured at 1489.5 m/sec. Thus, the sound velocity for the #6 fuel oil was slightly higher than that for distilled water at the same temperature.

The attenuation of sound in the fuel oil was initially determined by comparison of the strength of the echo return to that received in distilled water. The velocimeter was initially powered from a power supply which provided a 12.8 volt, peak to peak, return echo in distilled water. Upon immersion in the fuel oil, the transducer was found to be underpowered since an adequate threshold did not occur to distinguish the return echo. The power of the transducer was increased to provide an output signal of about 300 volts, peak to peak. This increased transducer power resulted in an echo return of 27.0 volts peak to peak, in distilled water. The velocimeter was then immersed in the #6 fuel oil, and an echo return of 6.0

volts, peak to peak, was obtained. This corresponds to a signal attenuation relative to distilled water of -13.1 db for the velocimeter travel distance of 0.672 meter, or -19.4 db/m.

Since this attenuation figure seemed rather high, it was decided to eliminate the possibility of low target strength of the velocimeter's corprene target by using a target of maximum impedance difference as provided by a water/air interface. The transducer was mounted on a tripod to be lowered beneath the surface of the liquid in the containers. The distance of the transducer below the surface was adjusted to correspond approximately to that of the travel distance of the velocimeter.

The tripod is distilled water with a water/oil interface target resulted in an echo return signal slightly in excess of 30 volts, peak to peak, as the signal was somewhat clipped on the oscilloscope. The travel distance was measured on the oscilloscope since the multiple return echos confused the counter. The tripod was then suspended in the fuel oil, and the time travel indicated by the counter corresponded to a travel distance of 0.76 meters. The echo return in the #6 fuel oil was measured as 6.0 volts, peak to peak. This corresponded to an attenuation of -14 db in 0.76 m, or -18.4 db/m in reference to the slightly clipped echo return in distilled water. Since the -18.4 db/m was in reference to a clipped return in distilled water, and is quite close to the -19.4 db/m attenuation obtained with the velocimeter, an attenuation of 18-19 db/meter seemed valid.

This attenuation of the 220 kHz signal was quite sever. To determine the attenuation at other transducer frequencies, the attenuation of 1 MHz and 50 kHz was determined. The attenuation of a 1 MHz signal was measured in the same manner as described above, and was approximately -94 db/m relative to distilled water. In testing the 50 kHz transducer, using the same method and without attempting to match the transducer, the echo return reduced from about 30 volts, peak to peak, in distilled water, to an indistinguishable return in fuel oil.

Since the attenuation values obtained in the thirty gallon container seemed quite severe, it was decided to eliminate possible causes of signal reduction. Factors associated with this apparatus which could have had an adverse effect on the measurement of attenuation were considered to be the short transmission distance which could involve near field effects, target reflectivity, and reflection of the signal within the container due to its geometry.

In order to verify the high attenuation values obtained, and to minimize the possible effects of the above factors, it was decided to construct a larger tank for measurement to insure operations in the far field and decrease the possibility of reflection. It was also decided to use a separate transmitter and receiver to eliminate the need for a target and the associated reflectivity characteristics.

A larger tank, particularly a longer tank, would also provide for measurement of signal strength at selected distances from the transmitter. This would provide a more accurate method of determining attenuation of the signal by providing progressively greater transmission distances.

To meet these conditions, a rectangular plexiglass tank measuring 21 inches wide, 21 inches high, and 96 inches long, was constructed. The maximum capacity of the tank was about 24.5 cubic feet, or about 200 gallons of fuel oil.

It was decided to measure attenuation at several frequencies in order to also gain an insight into the variation of absorption with frequency. Although the frequency of interest was 200 kHz, an estimated of attenuation at other frequencies would be helpful in the event it might be advantageous to utilize another transducer frequency. Since the initial measurements yielded a very high attenuation (-94 db/m) at 1 MHz, and entire loss of signal at 50 kHz, an additional frequency of 100 kHz was employed.

The 100 kHz transmitter was manufactured by ITC, and the receiver was a Model CH24 transducer manufactured by Gould, Inc. The 200 kHz transmitter and receiver were both Model No. TDC-0001, manufactured by MASSA, Inc. The output signal from the receiving transudcer was measured by a Techtronics Model 465 oscilloscope.

The attenuation measurements were conducted with the transmitter located 12 inches from the end wall of the tank, and the receiver positioned at successive locations of 12, 24, 36, 48, 60, and 72 inches from the transmitter. An initial receiver position of 12 inches from the transmitter placed operations in far field.

Tests were conducted first in fresh water, and then in the fuel oil, to eliminate any reflection effects caused by the tank geometry. A summary of test data is shown in Appendix A.

4.2 RESULTS

The attenuation data were initially analyzed by plotting the signal strength reduction in db versus distance from the transmitter for each frequency, 100 kHz and 200 kHz in water and in fuel oil. The attenuation measurements in water were then deducted from those obtained in the fuel oil. Since it was assumed that both conditions included identical geometric effects and spherical spreading loss, the difference between the signal loss in fresh water and that in oil at the same distance should yield the transmission loss due to absorption in fuel oil. These results are plotted in Figure 4.2.1 and 4.2.2 for 200 kHz and 100 kHz, respectively.

By plotting the data utilizing the curve fitting method of least squares, the slope of the oil minus water curve yielded an attenuation of 11.2 db/meter for 200 kHz and 4.0 da/meter for signal of 100 kHz.

The effect of transducer coupling in oil is indicated by the attenuation curve for 200 kHz. According to the curve, an initial loss of about 3 db occurred and was attributed to transducer coupling. In order to verify the attenuation values obtained by deducting the water results from the fuel oil results, it was decided to calculate attenuation from the test in fuel oil. The attenuation in fuel oil was determined by calculating only the spherical spreading loss and deducting it from the signal loss readings. Data points greater than 24 inches from the trans-

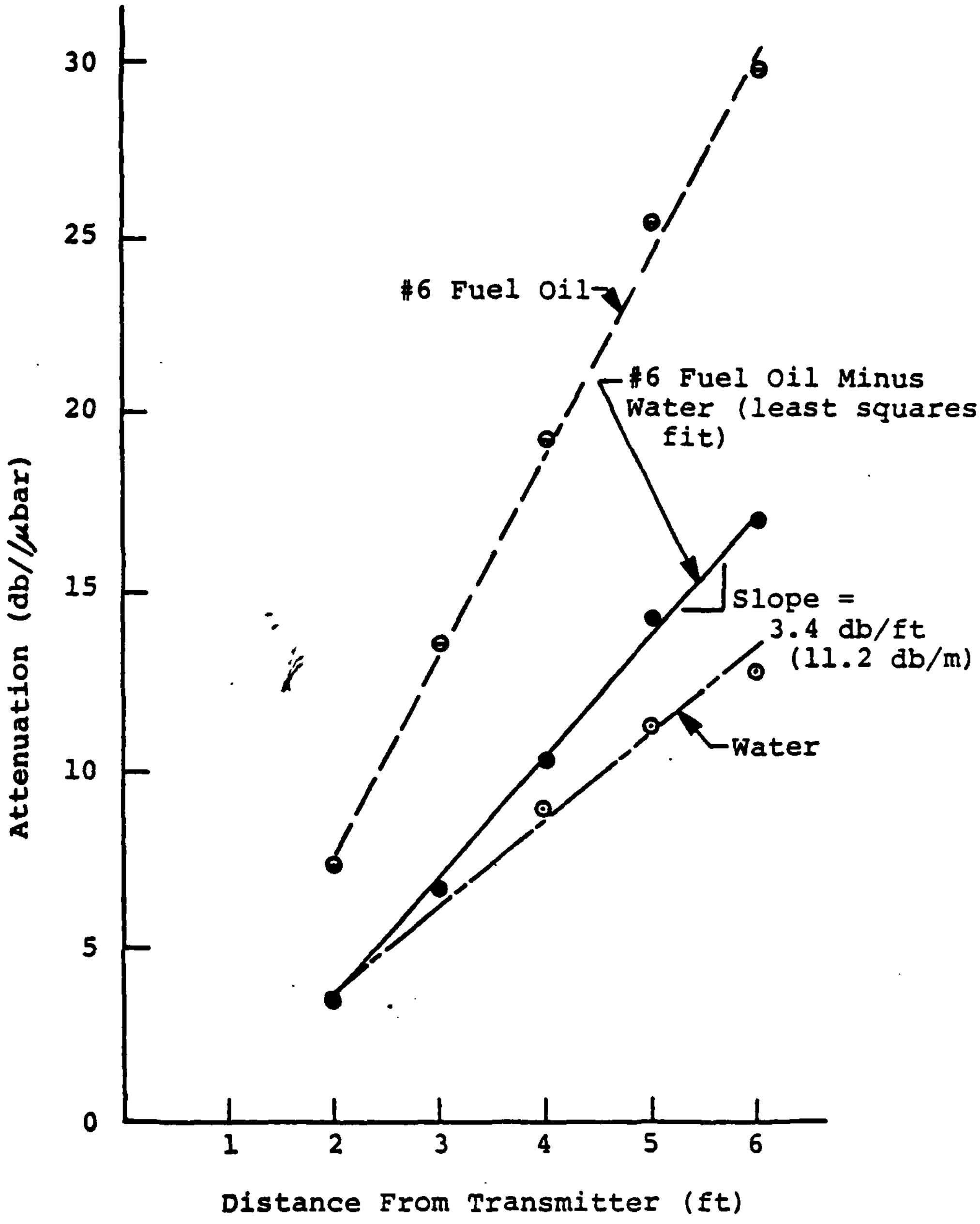


FIGURE 4.2.1 Attenuation in #6 Fuel Oil and Water at 200 kHz.

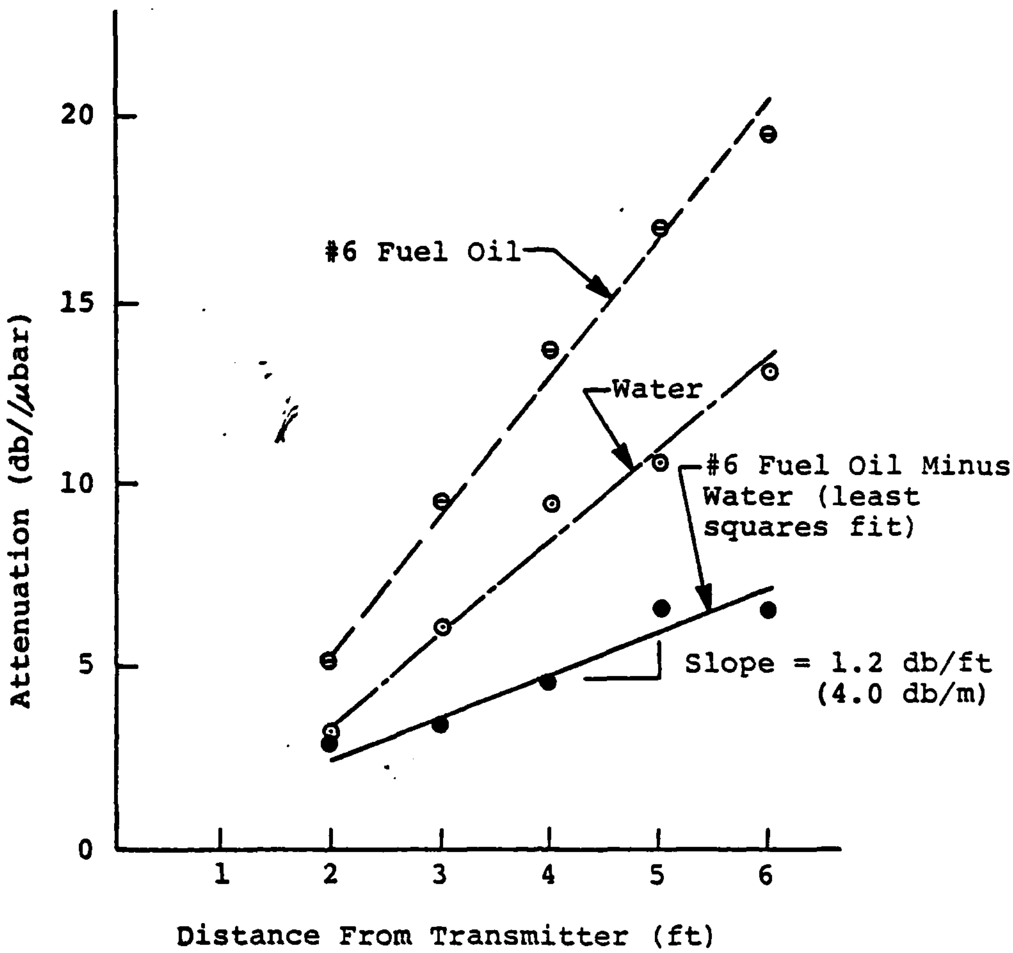


FIGURE 4.2.2 Attenuation in #6 Fuel Oil and Water at 100 kHz.

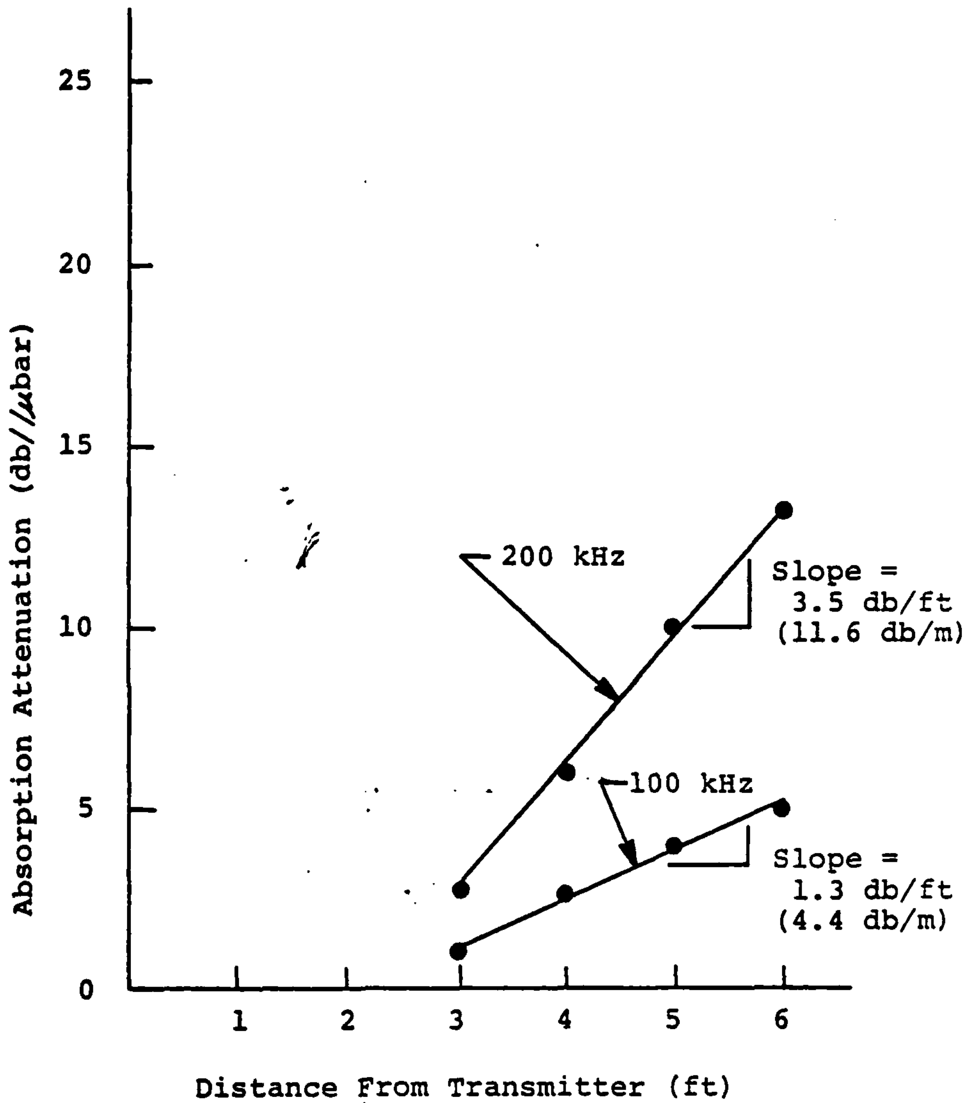


FIGURE 4.2.3 Absorption Attenuation in #6 Fuel Oil at 100 kHz and 200 kHz with a Reference Distance of 2.0 ft.

mitter were used to reduce any effects near the transmitter. Both spreading loss and signal reduction in db were calculated from a 24 inch reference distance. A plot of the data is shown in Figure 4.2.3.

As shown in Figure 4.2.3, the slope of the curve yields an attenuation of 11.6 db/meter for a 200 kHz signal in fuel oil, and 4.4 db/meter for a 100 kHz signal. These values were within a 0.4 db/meter of the values obtained by combining tests in water and fuel oil. For design purposes the attenuation values of 11.6 db/meter and 4.4 db/meter for 200 kHz and 100 kHz, respectively, were used.

The test results showed an anticipated increase in attenuation with frequency. The number of frequencies tested were not sufficient to establish a relationship of attenuation due to absorption as a function of frequency. However, the tendency toward a large increase in attenuation with increasing frequency was quite evident.

The attenuation due to absorption of sound in water as a function of frequency has been investigated quite thoroughly by a number of researchers,[109] and they have found that absorption of sound is a function of the frequency squared. However, the absorption in heavy petroleum products may be a linear function of frequency since the medium contains larger and more complex molecules than water.

In order to gain a conservative estimate of the magnitude of attenuation at higher frequencies, in view of the limited output of the SOTS-T unit as dictated by tanker safety requirements, a linear variation of attenuation with frequency was calculated from the data points. This calculation yielded an estimated linear absorption attenuation of 0.074 db/kHz. Consequently, at a frequency of 1 MHz, the absorption attenuation would be approximately 71 db/meter. Since the limitation of the SOTS output allowed only a total of 65 db/meter in an oil medium, the use of 1 MHz as a transducer frequency was eliminated.

5. CARGO MEASUREMENT SYSTEM

5.1 OBJECTIVE

The integration of the SOTS-T concept into a cargo measurement system has considerable potential since the SOTS-T has the ability to provide measurement functions for all anticipated conditions in normal tanker operations including those pending with IMCO regulations.

A cargo measurement system would be required to monitor liquid surface level, and when present, the occurrence of a water/oil interface. Measurement would be required during all normal tanker operations such as loading, transfer between tanks, transit, and unloading. The system, to comply with pending IMCO regulations, would be required to provide measurement functions as a slop tank monitor, stripping monitor, and measure departure ballast oil layer thickness. The system would be required to operate in a closed ullage environment, display measurement readings in remote locations, and be automatic with a minimum of operator interaction.

The accuracy of cargo measurement must be within current custody transfer standards. The system would be required to provide continuous measurement under adverse conditions of elevated temperatures during loading and impact during tank washing cycles. The system must take into account characteristics of the liquid medium such as variable composition and the presence of thermal gradients. The system must be able to operate within current vessel standards, comply with intrinsic safety requirements, integrate into existing tanker infrastructures, and provide acceptable maintainability.

5.2 SYSTEM

The design constraints of an acoustical measurement system were identified as attenuation due to absorption, determination of sound velocity in a variable medium, thermal variations in the oil due to elevated loading temperatures, thermal induced by heat transfer of the cargo during a voyage, resolution accuracy which is a function of transducer frequency, and energy output restrictions of the transducer imposed by intrinsic safety requirements.

The results of the laboratory testing indicated that attenuation due to absorption was the major acoustical constraint. The SOTS-T unit was limited to a maximum allowable transmission loss of 65 db/meter for operation in oil. With a measured absorption attenuation of 11.6 db/meter, and considering normal spherical spreading loss, an acoustic signal from the SOTS-T transceiver would be lost in only a few meters, allowing for two-way travel.

Consequently, the initial design concept of a single transceiver located on the bottom of a cargo tank and transmitting a signal which traveled a total two way distance of 60 meters, was not practical. The high absorption attenuation of an acoustical signal in oil dictated that the transmission path of the signal be greatly reduced. A configuration which would allow a smaller transmission distance between transceiver and interface was that of a vertical line of multiple transceivers positioned at regular intervals. By using the program capabilities of the

SOTS-T microprocessor, the transceiver array would measure interface location only between the transceivers where the interface occurred. This configuration is shown in Figure 5.2.1. To measure the total height, d_T, of a liquid in a tank, the SOTS-T program was required to sense the location of an interface between any two transceivers, measure the distance, r_i, of the interface from the lower, or active transceiver, and add this distance to the fixed distance, d_i, of the active transceiver from the bottom of the tank.

The optimum separation interval between transceivers in the SOTS-T configuration was calculated considering normal spherical spreading loss and an absorption loss of 11.6 db/meter at a transducer frequency of 200 kHz. A maximum interval of 2.0 meters yielded a two-way transmission loss of 59 db in oil. This was 6 db below the allowable transmission loss in oil of 65 db, and resulted in an increased reserve for signal detection of 16 db.

At a transceiver interval of 2.0 meters, a maximum cargo tank depth of 30 meters would require a vertical array constructed of at least 15 transducers. From a transducer cost standpoint, the hardware cost for additional transducers would be nominal since 200 kHz transducers are commonly available and relatively inexpensive.

The close spacing of the transceivers was beneficial, and in fact necessary, in overcoming the two major design constraints of variable sound velocity in crude oils and the presence of thermal gradients.

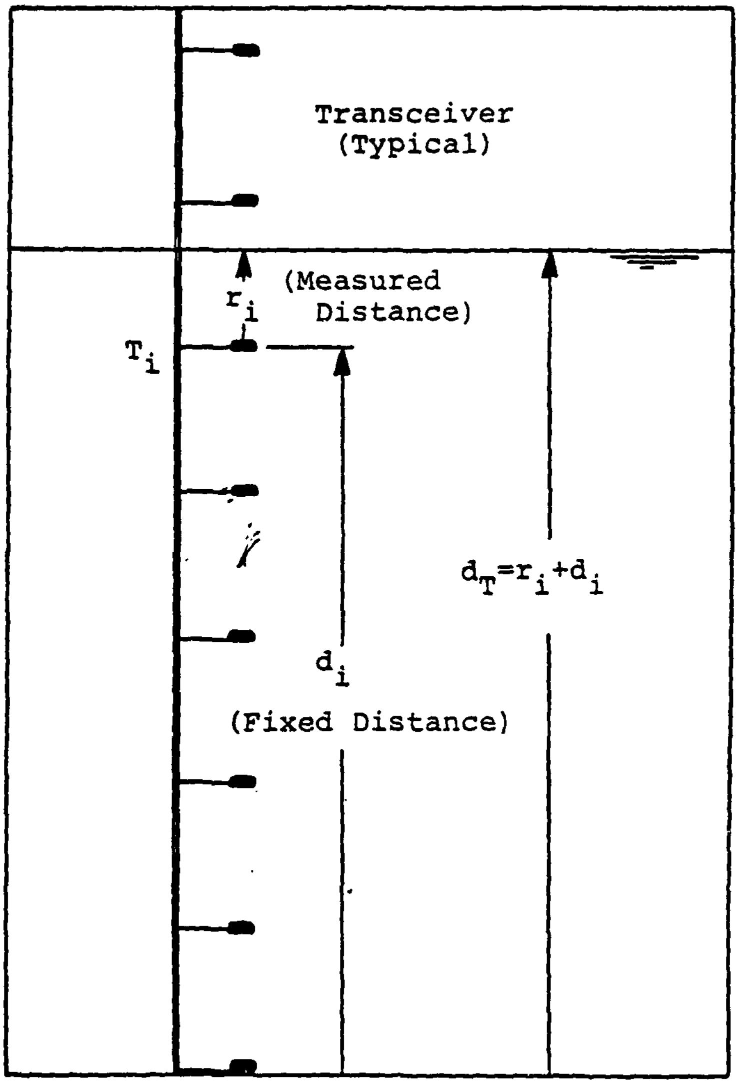


FIGURE 5.2.1 Vertical Transceiver Array Concept to Measure Total Depth, d_T.

As mentioned in the previous section, an accurate calculation of the sound velocity in crude oils from normal API parameters was not possible due to the wide variations in the structural composition of crude oils. However, with transceivers positioned at fixed intervals, an in-situ sound velocity may be determined near the active interface measuring transceiver utilizing several of the transceivers in the array. The most advantageous location for sound velocity determination would be in the transceiver interval immediately below the interval in which the liquid level interface occurred. With intervals of 2.0 meters, an in-situ sound velocity would be determined only a few meters below the interface.

The problem of thermal gradients would also be minimized by the use of a vertical array of transceivers. Since an interface would be measured only a short distance from a transceiver located at a fixed distance from the tank bottom, any thermal gradients in the tank below the active transceiver would not effect acoustic measurements.

The requirement for the measurement of in-situ sound velocity modified the basic transceiver array as shown in Figure 5.2.2. The transceiver elements are positioned in a staggered pattern 1.8 meters apart. Each transceiver station consisted of two transceivers, one facing up and the other facing down. The downward directed transceivers were necessary to provide a direct transmission path for in-situ sound velocity determination.

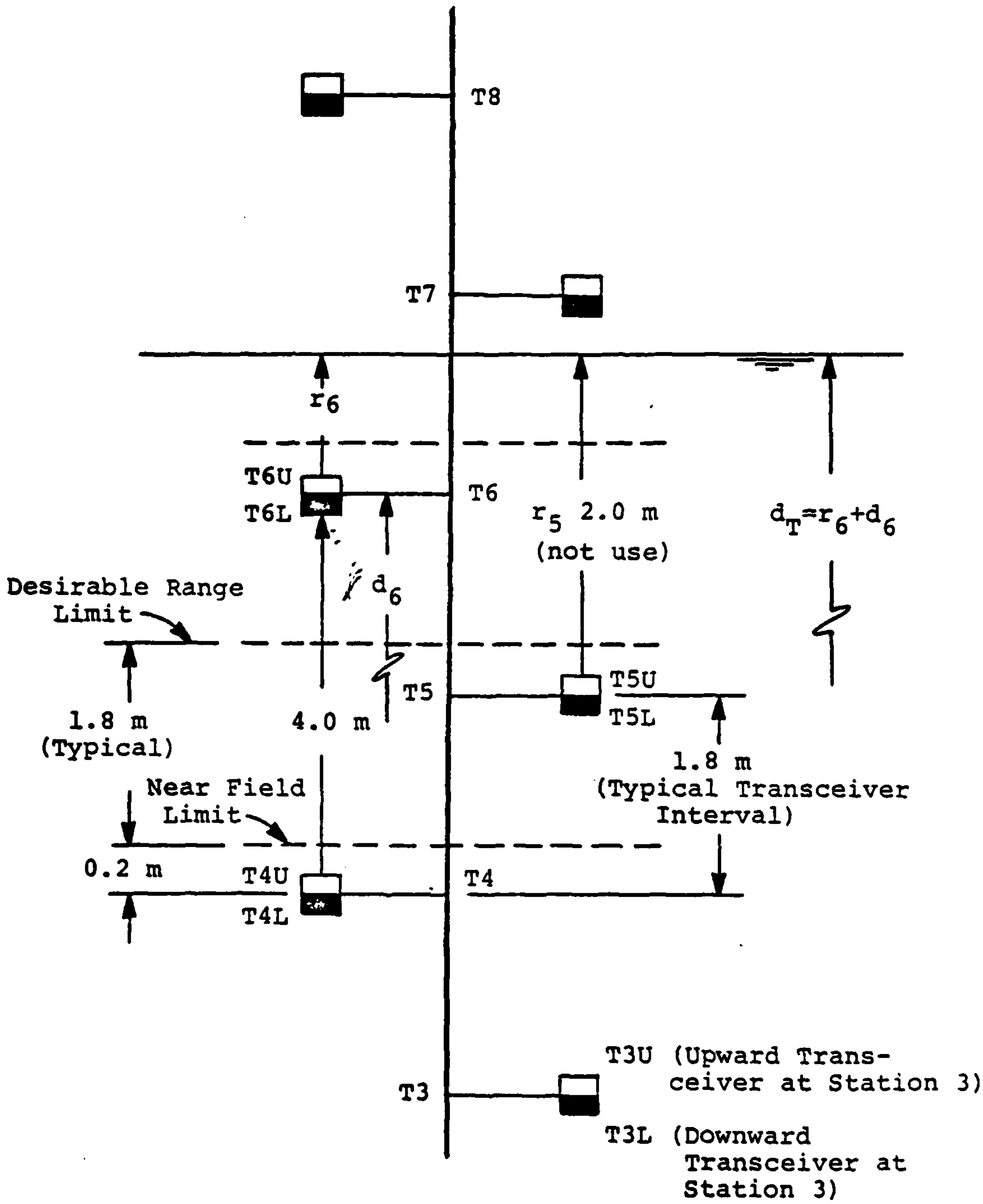


FIGURE 5.2.2 SOTS-T Vertical Transceiver Array Configuration.

The staggered position of the transceiver also provided for two transceivers to be directly below any interface. This concept was utilized to avoid the near field effects which would decrease the accuracy of measurement near a transceiver surface. The logic of the SOTS-T unit would determine if the interface was within the desirable range, beyond the near field distance and within the optimum receiving distance. If the interface was not within the desirable range, the SOTS-T program would switch to the signal return of the other transceiver which would be receiving the signal within the desirable range. For design purposes, the near field limit was established at 0.2 meters from a transceiver surface. The optimum receiving range was established at less than 2.0 meters.

Utilizing the speed of the SOTS-T microprocessor, it was decided to adopt a dual search mode for detecting and measuring both interfaces. The first search mode was for the surface level, the oil/air interface, and the second for the lower water/oil interface.

Figure 5.2.3 shows the SOTS-T elements for the detection and measurement of a single liquid surface interface corresponding to the first search mode. The location of the interface between transceivers was first determined. Pairs of transceivers consisting of an upward and downward transceiver would be activated vertically, starting at the bottom transceiver and progressing vertically in a stepwise fashion by the program until signal transmission between

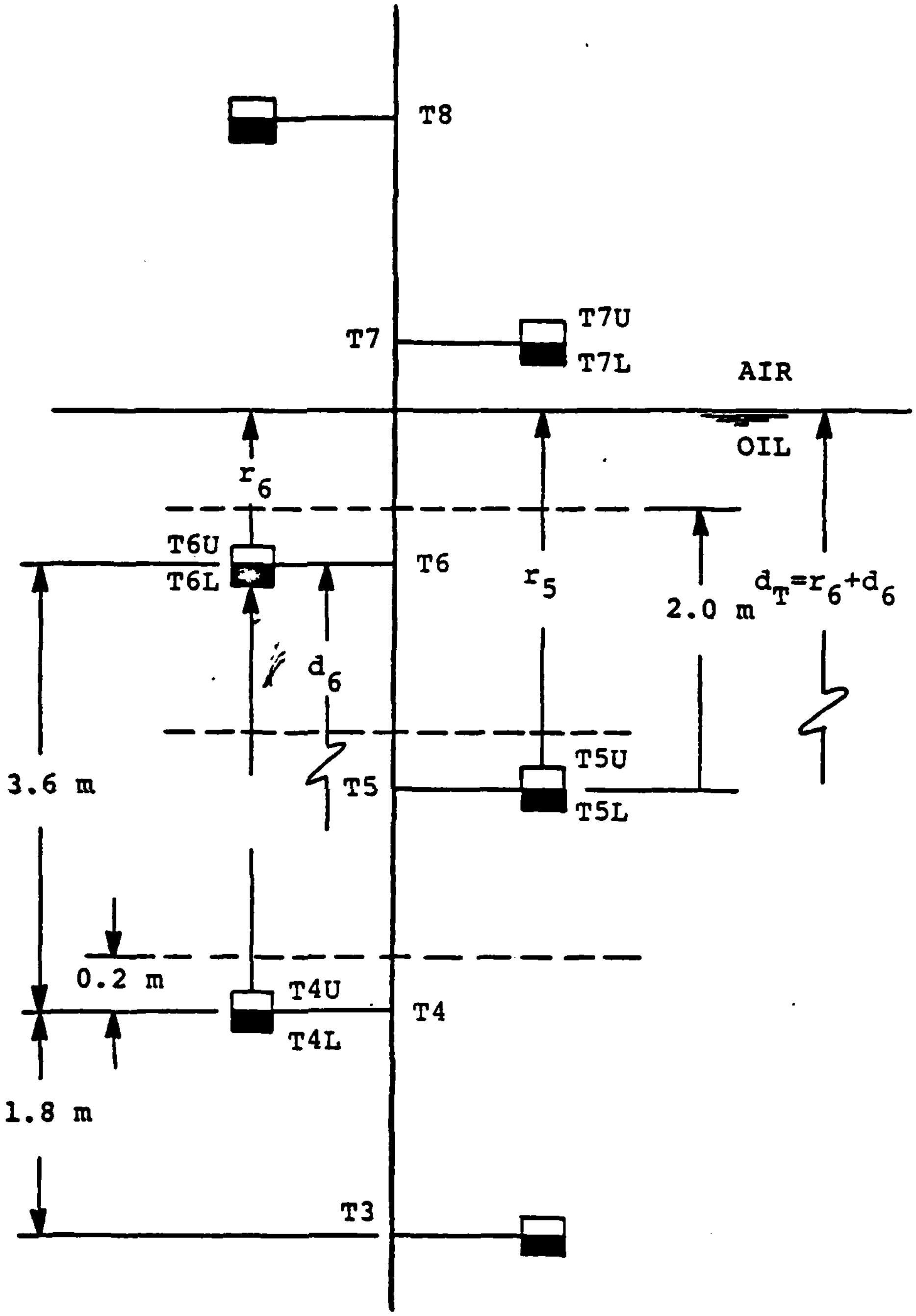


FIGURE 5.2.3 First Search Mode, Oil/Air Interface.

transceiver pairs did not occur. In Figure 5.2.3, the interface is shown between transceiver stations T6 and T7. In the upward progression of search, the T4U-T6L transmission path would be completed and the next path between T5U-T7L would be interrupted by the liquid surface and a corresponding lack of received signal. The program would then decide that the transceiver station T7 - 1 = T6 was directly below the interface. With the interface located, the next step was to determine in-situ sound velocity. The program then would measure the travel time of the signal from T6 - 2 = T4U to T6L. The program would compute the sound velocity by dividing the fixed distance, b, between the upper and lower transceivers by the travel time of the signal, and store the sound velocity value in memory.

The program would then activate transceiver T6U, track the sampling window to the interface, measure the time for an echo return from the interface, compute the distance, r_6, using the stored in-situ sound velocity, and store r_6 in memory. The value of r_6 would be compared to determine if it was in the desirable range, 0.2 meters to 2.0 meters.

If r_6 was within the desirable range, the program would then resample this transceiver, T6U, for a longer period of time to establish more accurate results, recompute r_6 (the distance from T6U to the interface) and store this value in memory.

The program would then compute the total distance from the bottom of the tank to the interface, d_T, by adding r_6 to the fixed distance, d_6. The value of d_T would be stored in memory and displayed in the cargo control room at surface level.

If r_6 was not within the desirable range the program would activate T6U - 1 = T5U, repeat the procedure to measure the distance, r_5, from the transceiver T5U to the interface, and compute d_T.

The next search mode of the program was to detect and measure the location of a water/oil interface. The potential position for a water/oil interface depends upon the measurement situation. The interface may be located near the bottom of a cargo tank where water has accumulated after a long voyage. It may appear near the top surface beneath a thin layer of oil, as would be the case for departure ballast. It may appear midway between these two extremes, as would be the case in a slop tank.

The most general case, that of a water/oil interface in the mid-region of the vertical array, well below the surface and above the bottom of the tank, was considered first. This situation is shown in Figure 5.2.4. The second interface search mode would begin by activating the upward transceiver and progressing vertically. When an echo return was sensed at a transceiver, the program would halt the search and process the data to determine the travel distance to the interface.

Referring to Figure 5.2.4, the first transceiver to

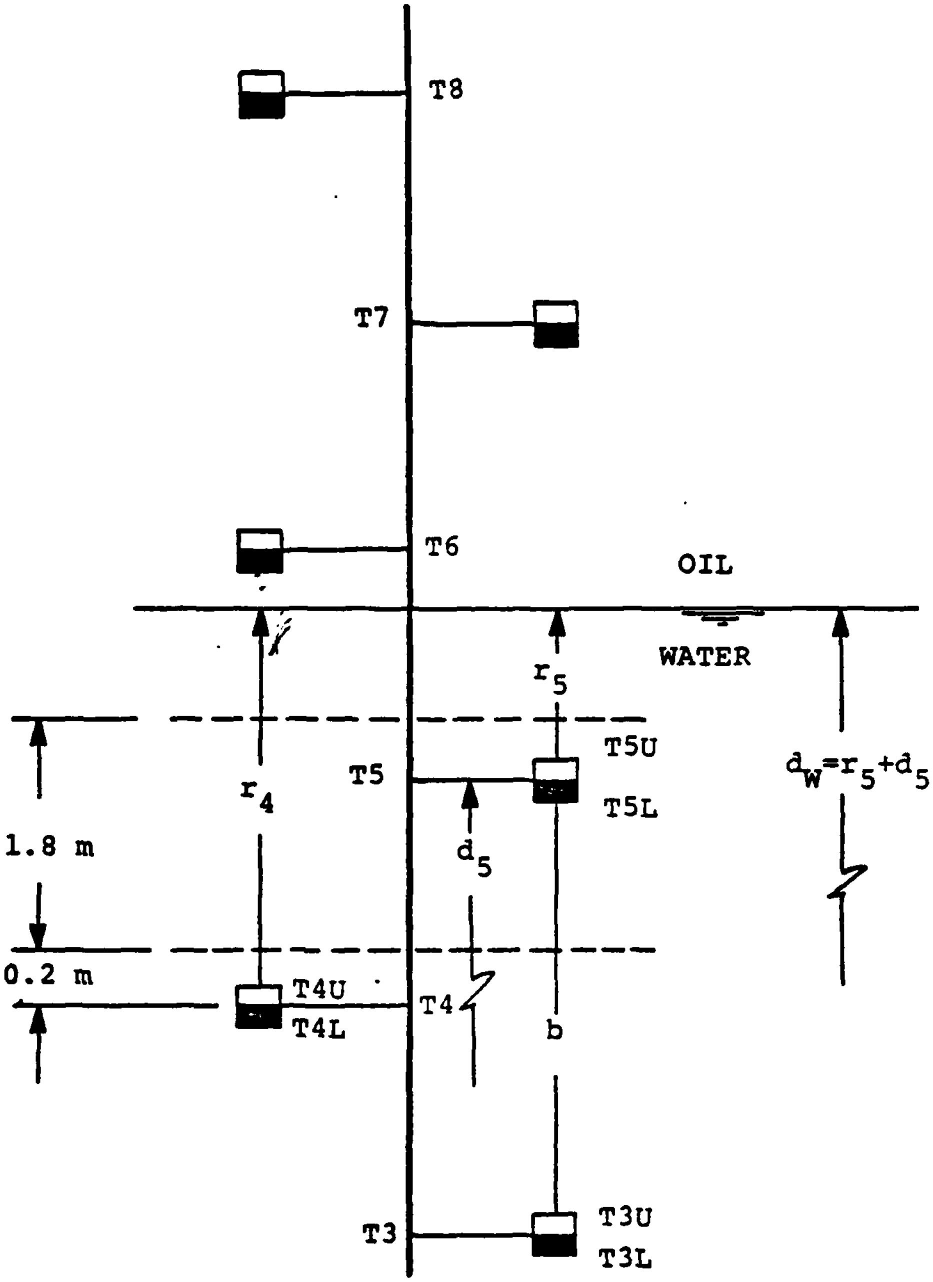


FIGURE 5.2.4 Water/Oil Interface at Mid-Region.

receive an echo may be T4U. If sufficient signal returns to T4U the distance, r_4, would be computed using a stored sound velocity constant and stored in memory. The program would determine if r_4 was less than or greater than 2.0 meters. If r_4 was greater than 2.0 meters. the program would then step up to the next transceiver T4U + 1 = T5U, sense an echo return, measure the echo return time, and with the stored sound velocity constant, compute the distance, r_5. The distance r_5 would be compared to determine that r_5 was less than 2.0 meters. If so, the program would determine that T5U was the transceiver receiving a signal return within the desirable range. A stored sound velocity constant was used to speed the program sequence and was a coarse determination of the transceiver receiving a return within the desirable range. The program would then proceed to measure in-situ sound velocity for an accurate measurement of the distance to the interface.

If r_4 above was determined to be less than 2.0 meters, the program would go directly into the in-situ sound velocity determination to compute an accurate distance, r_4, to the interface.

The upper and lower transceiver pair made up of the lower transceiver at the interface measurement station, T5L, and T5L - 2 = T3U would be activated to measure travel time and compute in-situ sound velocity. This value of in-situ sound velocity would be stored in memory.

The program would then measure the travel time to the interface from the active transceiver, T5U, and compute the distance, r_5, using the previously determined in-situ sound velocity. This value would be added to d_5, the fixed distance from the bottom of the tank to transceiver, T5U, to obtain d_W, the depth of the water/oil interface from the bottom of the tank.

A computation of oil thickness in the tank would be computed by subtraction, using the stored values of d_W and d_T to display as $d_T - d_W = t$ in the cargo control room.

To account for the situation in which a second interface did not occur, such as a cargo tank after loading, the value of d_W obtained in the second search mode would be compared to d_T, obtained from the first search mode. If $d_W = d_T$, this would indicate that both search modes have detected the same interface and d_W would be given the value of zero, stored in memory, and displayed in the cargo control room as $d_W = 0$.

In the above case, where the water/oil interface occurred well above the bottom of the tank, transceivers were available for the determination of in-situ sound velocity. However, when a water/oil interface occurs near the bottom of a tank, transceivers may not be available for in-situ sound velocity determination. This case is shown in Figure 5.2.5.

In this figure, the second search mode would sense that the first echo return occurred from transceiver T1U. The program would follow the normal sequence and compute

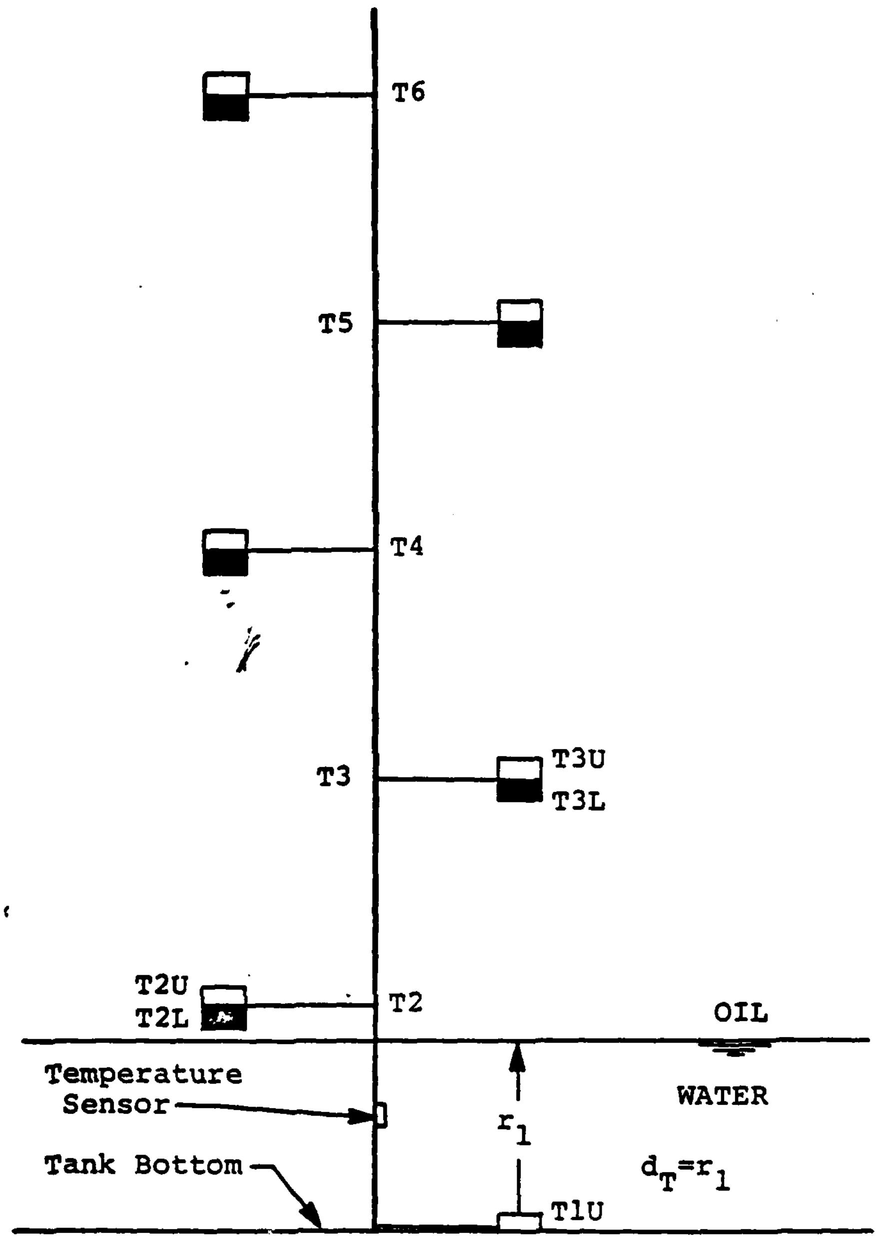


FIGURE 5.2.5 Water/Oil Interface Near Tank Bottom.

r_1 from a stored sound velocity constant. The r_1 would be compared to determine if it was less than, or greater than 2.0 meters. In this case, r_1 is less than 2.0 meters. The program would determine that T1U is the interface transceiver.

The next step would be to measure in-situ sound velocity with an upper and lower pair of transceivers directly below the interface transceiver. However, such a pair does not exist below the bottom transceiver, nor below the transceivers T2U and T3U. Consequently, the second search mode would have the decision that if the interface transceiver was T3U or greater, the normal in-situ sound velocity sequence would proceed. However, since the interface transceiver, in this case, is below T3U, the program would proceed to compute a sound velocity utilizing the input from a digital temperature sensor located near the bottom of the tank. The computation of sound velocity would be from a recognized equation relating sound velocity as a function of temperature.

Then following the normal sequence, the program would compute r_1, add it to d_1, which is zero, to determine the distance, d_W, and display it in the cargo control room.

The next case occurs when the water/oil interface was near the oil/air interface. This case would occur only in the slop tank and departure ballast tanks. For analysis purposes this case was divided into three situations, depending upon the nearness of the water/oil and oil/air interfaces.

The first of these situations occurs when the water/oil interface interval is directly below a transceiver receiving any echo from an oil/air interface. This is shown in Figure 5.2.6. The oil/air interface is above the transceiver, T11U, and the water/oil interface above T10U. In the normal first search mode for surface interface location, the program would determine that T11U was the transceiver below the oil/air interface. The program would proceed to determine the in-situ sound velocity by measuring the travel time between the upper and lower transceiver pair, T9U-T11L. In this case, the in-situ sound velocity measured would not be that of the oil, but that of the water. However, taking into consideration that the oil layer thickness would not be greater than a maximum of 4.0 meters, and that the sound velocity of oil is within 10% of that of water, the error introduced would be small. In addition, this situation would not occur in a cargo tank where custody transfer accuracy is required. The normal first interface search mode would continue, and the total depth to the oil/air interface determined.

The second interface search mode would proceed normally, activating the transceivers in sequence vertically until an echo return was detected. Referring to Figure 5.2.6, this would occur with transceiver T9U, if the echo return has sufficient strength. The program would compute r_9 using a stored sound velocity constant. If r_9 was

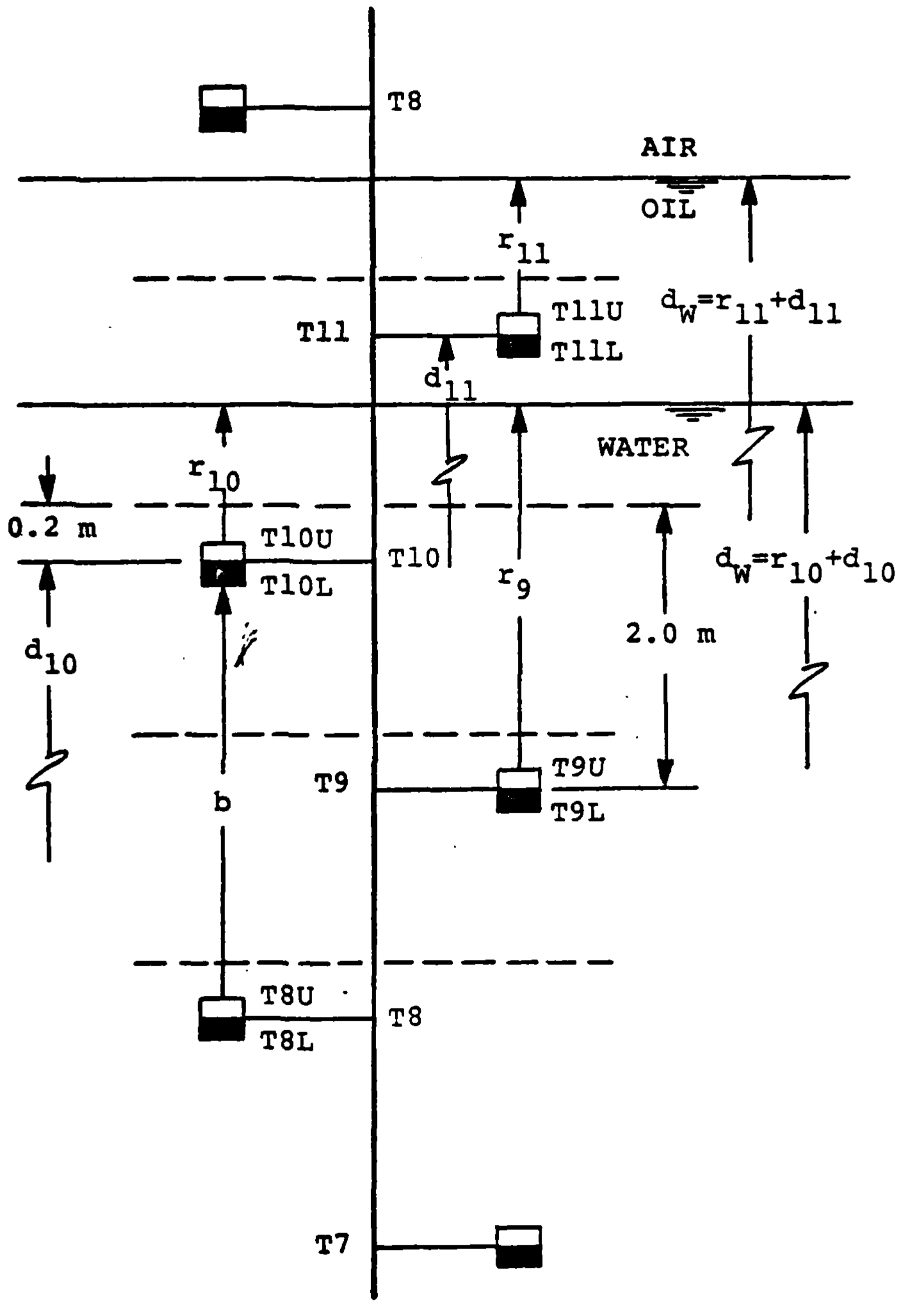


FIGURE 5.2.6 Water/Oil Interface Directly Below Transceiver Receiving an Echo Return from a Oil/Air Interface.

greater than 2.0 meters, the program would progress to the next transceiver, T9U + 1 = T10U, and sense an echo return. The program would compute r_{10} using the stored sound velocity constant. If r_{10} was less than 2.0 meters, the program would select T10U for sampling, since r_{10} would be within the desirable range for the transceiver. The program would proceed normally and compute the in-situ sound velocity from the upper and lower transceiver pair, T10U - 2 = T8U and T10L. The in-situ sound velocity would be computed from the travel time and store in memory. The distance to the water/oil interface would then be computed by adding r_{10} to d_{10} to obtain d_W.

The only difference in this sequence was the use of an in-situ sound velocity of water for computation of distance to the oil/air interface. The second search mode was the same as a mid-region search. The main point is that the second search mode would not progress beyond transceiver T10U, which would lead to the measurement of the same interface.

The next situation occurred when both the oil/air interface and the water/oil interface were located above the same transceiver. Two variations may occur. The two interfaces may be sufficiently close together that they both occur in the same time gated window, or they may be separated sufficiently to not do so. These variations could occur in a slop tank or departure ballast tank with a thin layer of oil.

The situation when both interfaces occurred within the same time gated window was analyzed first, and is shown in Figure 5.2.7. In the normal first interface search mode, the transceiver below the oil/air interface would be located, transceiver T12U. Then, the in-situ sound velocity would be computed by measuring the travel time between the upper and lower transceiver pair directly below the interface transceiver. As mentioned previously, the measured in-sit sound velocity would be that of water. However, the valve would be acceptable for the measurement of thin layer of oil.

The normal first interface search mode would track the time gated window up from the transceiver until an echo return was detected. It would then sample the return signal in the window by computing the centroid of the wave packet. It would process the data, determine the distance to the interface, compute d_T, and proceed to the normal second interface search made. However, this sequence did not allow for two interfaces within the same time gated window. Consequently, for this condition it was decided that the first interface search mode would be modified to include an examination of the wave packet in the window for two interfaces using the basic SOTS dual interface detection program.

Referring to Figure 5.2.7, the normal first interface search mode would locate the transceiver below the surface, the oil/air interface, transceiver T15U as before.

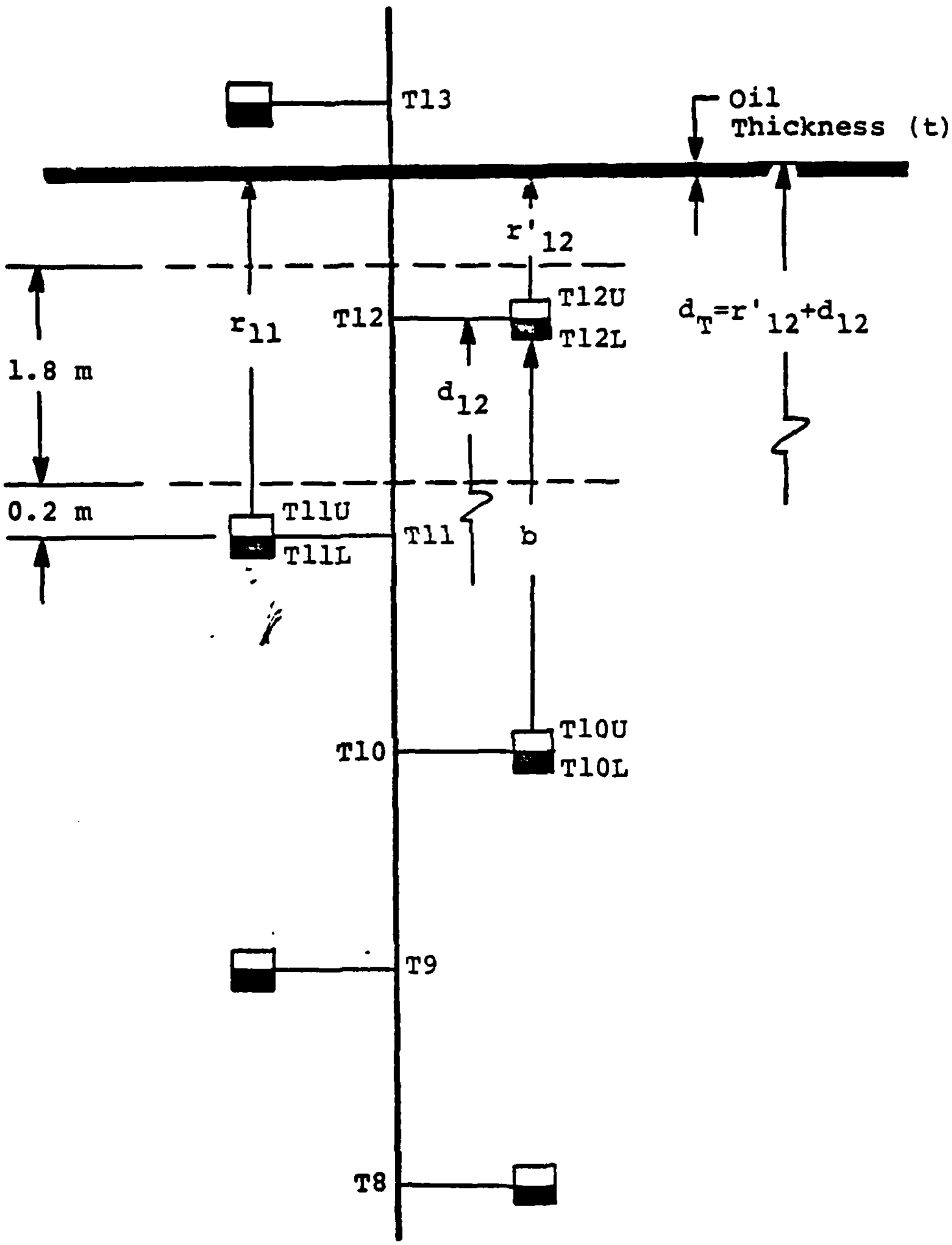


FIGURE 5.2.7 Thin Oil Thickness, Oil/Air and Water/Oil Interfaces Both Occur in Same Sampling Window.

In-situ sound velocity would be determined between T10U and T12L. The program would return to T12U. The SOTS dual interface subroutine would then track, locate, and examine the echo return in the time gated window for two interfaces.

In the basic SOTS dual interface subroutine, the centroid of the entire wave packet would be computed to locate the dominant oil/air interface. The next step would be to determine the earlier, weaker, water/oil interface by locating the centroid of the leading truncated portion of the wave packet. The program would decide if a water/oil interface did or did not exist by the presence or absence of second interface echo return energy in the truncated portion. If a second interface was detected, the subroutine would proceed to compute a second centroid. The oil layer thickness would be computed by the SOTS subroutine by the difference in travel times to the two interfaces using the in-situ sound velocity. Since two interfaces were detected, the program would not initiate a second interface search mode. It would proceed to compute r'_{12} d_T and d_W. The distance, d_T, would be obtained by adding r'_{12} to d_{12}, and the distance, d_W, would be obtained by subtracting the thickness, t, from d_T. The values of d_T, d_W, and t would be stored in memory and displayed in the cargo control room.

The next condition analyzed was when both interfaces were above the same transceiver, but sufficiently separated to not occur in the same time gated window. This condition is shown in Figure 5.2.8. The program would proceed as before, locate the transceiver below the oil/air interface, transceiver, T12U. The in-situ sound velocity would be computed with the travel time between T10U and T12L. The next step of the first interface search would use the SOTS dual interface subroutine, as before.

In the condition of Figure 5.2.8, a second interface would not be detected since the two interfaces are sufficiently separated. The SOTS subroutine would not detect a second interface due to the absence of a second interface echo return in the truncated portion of the wave packet. The program would then compute the distance, r_{12}, to the centroid, using the in-situ velocity. The distance, r_{12}, would then be compared to determine that it was greater than 0.2 meters, and less than 2.0 meters, indicating that the interface was within the desirable range.

If r_{12} was within the desirable range, the program would proceed to store r_{12} as the first distance. Since the SOTS subroutine did not detect a second interface within the window, the program would then proceed to track beyond r_{12} until another echo return was detected, or it had tracked beyond a time corresponding 2.0 meters.

In Figure 5.2.8, the second echo return would be detected at the distance corresponding to r'_{12}. The program would halt the tracking sequence and sample the echo return with normal single centroid computation sequence.

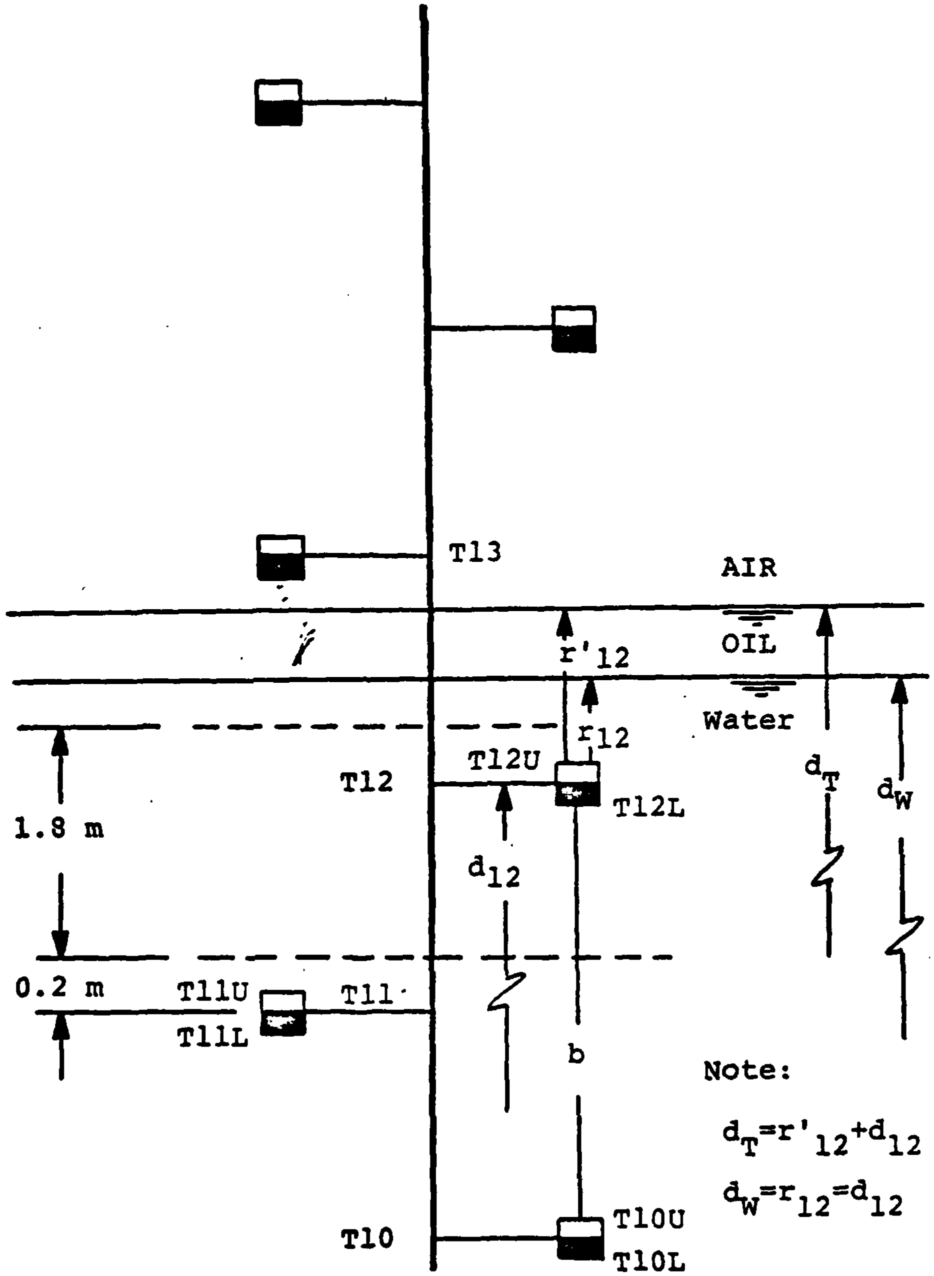


FIGURE 5.2.8 Two Interfaces Above the Same Transceiver. Both Interfaces Not Occuring in the Same Sampling Window.

The normal program would proceed, and the distance r'_{12}, would be determined and stored as the second distance.

The second distance, r'_{12}, would be added to d_{15} to obtain d_T. The first distance, r_{12}, would be added to d_{15} to obtain d_W. The program would compute oil thickness by $d_T - d_W = t$. These values would be stored in memory and displayed in the cargo control room.

If a second interface was not detected, the normal second interface search mode would be activated.

If, during the above sequence, r_{12} was determined to be less than 0.2 meters, as shown in Figure 5.2.9, the program would store this value and proceed as before to detect and compute r'_{12}. After this sequence, the program would proceed to move down to transceiver T11U, and compute r_{11}. The distance, r_{11}, would be compared to determine that it was less than 2.0 meters and greater than 0.2 meters--within the desirable range. If it was, as shown in Figure 5.2.9, then r_{11} would be sampled for a longer period. Then r_{11} would be computed, stored, and added to d_{11} to obtain d_W. The oil thickness, t, would be computed and d_T, d_W, and t, displayed in the cargo control room.

The case may occur when a second interface, water/oil, was absent. In this case a second interface would not be detected with the SOTS dual interface routine, and the program would use the distance to the first interface as r'_{12} and add it to d_{15} to obtain d_T. The program would then proceed to the normal second interface search mode.

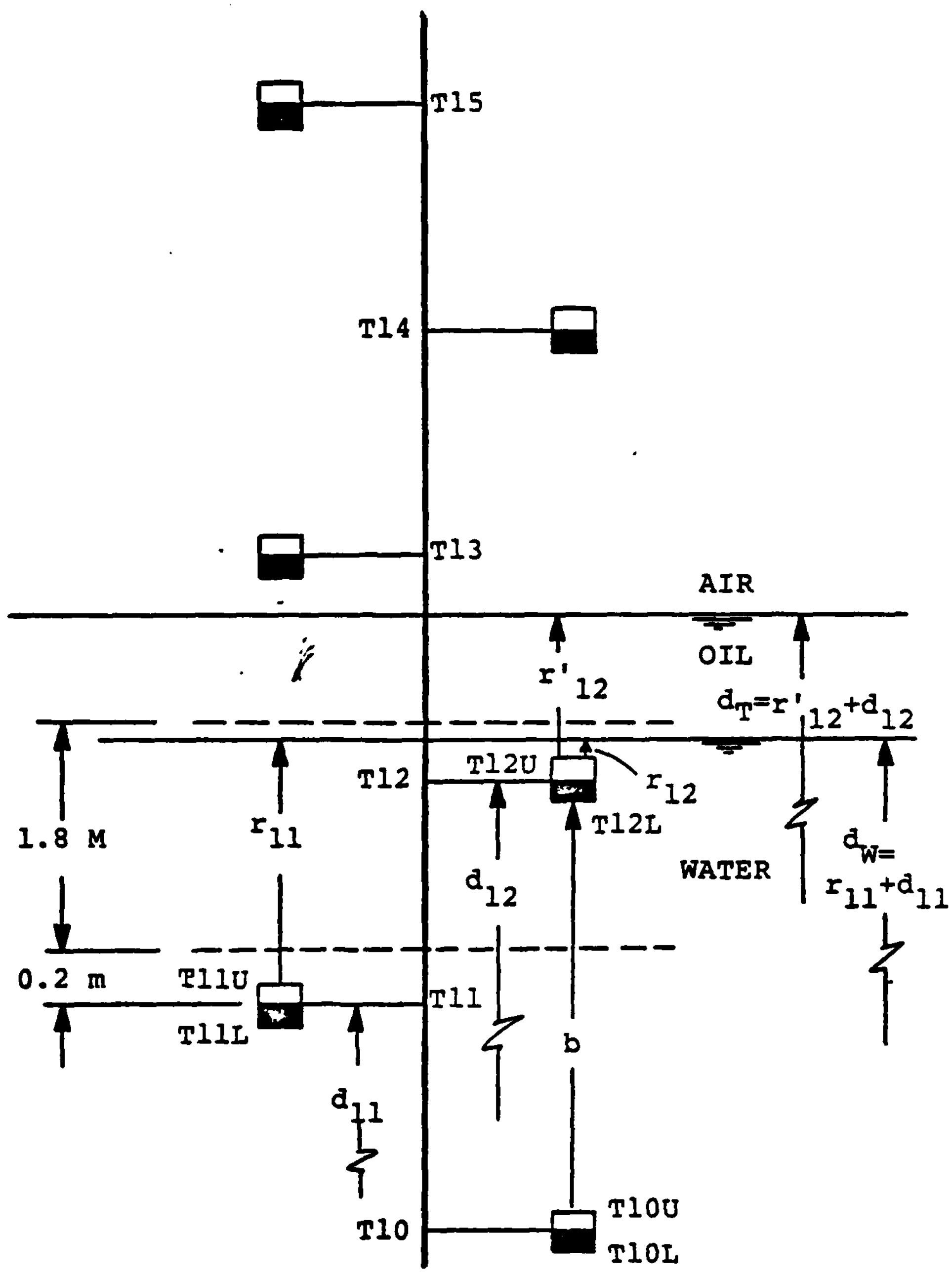


FIGURE 5.2.9 Two Interfaces Above the Same Transceiver with Lower Interface Within Near Field Limit.

The value, d_W, obtained in the normal sequence interface search mode would be compared to d_T. Since d_W would be equal to d_T, the program would determine that $d_W = 0$. The value of d_T, $d_W = 0$, and $t = 0$, would be stored in memory and displayed in the cargo control room.

In order to save program time, and speed the measurement cycle, it was decided to include the SOTS dual interface subroutine only for the slop tank and departure ballast measurements. The selection control in the cargo control room for the slop tank and the departure ballast measurement mode, would automatically include this subroutine in the measurement program.

The selection control for segregated ballast would enable only the first interface search mode since a second interface would be known not to exist. However, to check the segregated ballast tanks for evidence of oil, the departure ballast measurement mode could be employed by manual override.

This completes the operational logic of the SOTS-T configuration for all of the measurement cases for tanker operations.

The construction and placement of the vertical transceiver array on board an oil tanker was influenced by the operational criteria of maintainability and robustness for protection from the impact of tank washings.

It was decided--for maintainability--that the transceivers should be mounted on a removable vertical support structure. The transceiver array could then be constructed as a module and replaced with a spare if necessary.

A vertical array unit is shown in Figure 5.2.10. The transceiver support arms are staggered on an 80° offset between alternating transceivers. The length of the support arms are such that at a 80° offset, the sonified area of a horizontal plane 2.0 meters above any transceiver, would be clear of any structure which could produce a direct echo return. The transceiver elements were flush mounted in enclosure plates to minimize the effects of washing impact. The main column of the support structure was fitted with guides so that the unit was positioned and held in place by the vertical tank rail. The tank guide rail could be an existing vertical tank stiffener, or installed for the transceiver array.

A layout of a complete cargo measurement system is shown in Figure 5.2.11. A transceiver array was located at the aft bulkhead of each tank to provide measurement data when the tanker is trimmed by the stern for loading and unloading. This position also was required for the functioning of the stripping monitor. For intrinsic safety, the SOTS-T electronics unit and power supply were located in the cargo control room, a nonhazardous location. The cable distribution system and transceivers would be the only elements in a hazardous locations.

The SOTS-T program would sample each tank in a sequential pattern. As a result, the amount of electrical

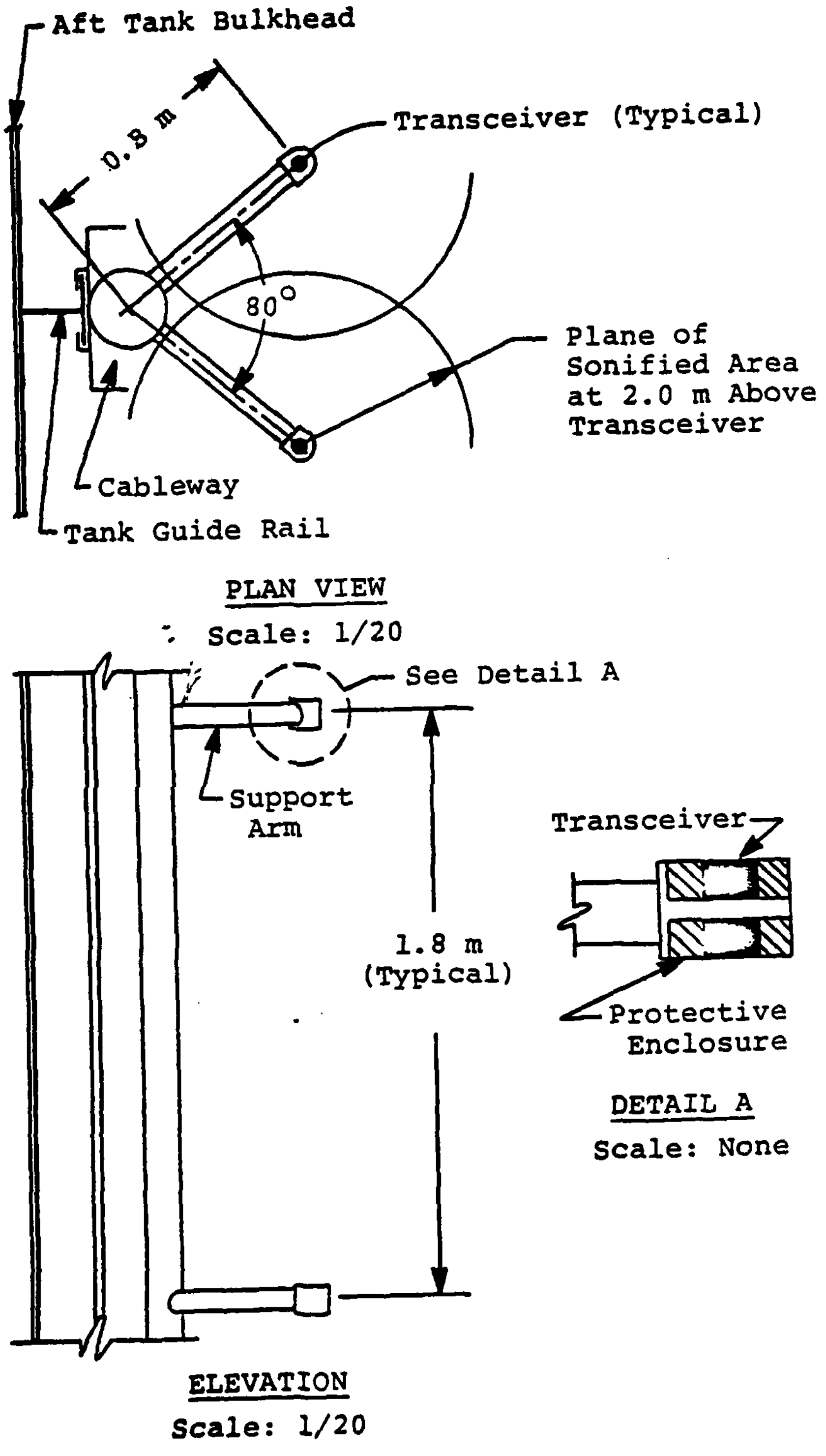


FIGURE 5.2.10 Tanker Vertical Transceiver Array.

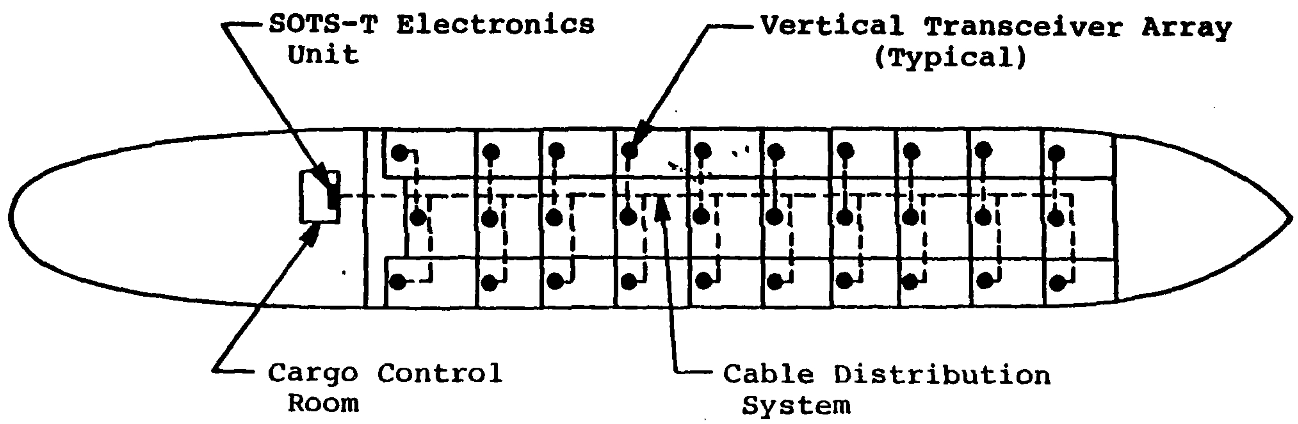


FIGURE 5.2.11 Cargo Measurement System Schematic.

energy in a hazardous location, would not exceed that needed to drive a single transceiver at any given time. The sequential sampling pattern would be the normal mode of operation. Manual override would provide continuous sampling of any tank or sequential sampling of selected tanks, as would be the case during transfer between tanks. Slop tank and departure ballast tank measurements would have separate select controls which would include the dual interface search subroutine to detect thin oil layer thickness. The speed of the SOTS-T microprocessor, and the slow rate of liquid level change on an oil tanker, make the sequential mode of tank sampling both feasible and economical.

6. CONCLUSIONS AND RECOMMENDATIONS

The adaptation of the basic SOTS concept to a SOTS-T configuration suitable for oil tanker cargo measurement was determined to be feasible. The SOTS-T has the capability to perform measurement functions within the constraints of tanker infrastructure and normal operations. The SOTS-T was designed to locate and measure both the oil/air and water/oil interfaces in cargo tanks and a variety of other measurement situations. The design meets all of the requirements for cargo load level gauging during loading, transit, and unloading operations. In addition, the SOTS-T has the capability to perform the special pollution control functions required under pending IMCO regulations. The SOTS-T could function as a monitor for stripping operations, slop tank water/oil interface location, and oil quantity in departure ballast tanks.

The SOTS-T configuration has the capability to operate under closed ullage conditions, measure within custody transfer accuracy requirements, operate automatically--thus eliminating the operator experience factor--and provide memory capability for data storage and retrieval. The proposed design of the SOTS-T configuration provides for robustness and maintainability.

The developmental influence of international regulations, law and liability organizations, were found to provide the necessary context and incentive for the implementation of oil tanker technology, such as the SOTS-T application.

The international regulations of IMCO obligate, and provide enforcement provisions, for vessel owners to design and employ equipment required to prevent oil pollution. International law, under formulation by UNCLOS III conferences, place additional constraints on tanker owners to operate their vessels in a manner that ensures continued "freedom of passage," traditional with ocean shipping. Liability organizations provide incentives for vessel owners to adhere to international regulations by denying liability protection to vessels which are not in compliance with IMCO.

The SOTS-T configuration has the potential to be integrated into a cargo measurement system for the monitoring of cargo tanks, slop tanks, and ballast tanks. The SOTS-T microprocessor has the capability for sequential sampling of tanks for economy and safety; manual sampling of single tanks; and selected sequential sampling of tanks during transfer between tanks.

The cost of the SOTS-T system would obviously be greater than that of the traditional hand taping method. However, when viewed in the context of pending IMCO regulations, world concern sufficient to propose redefinition of the traditional concept of "freedom of passage," escalating cost of oil, and lack of viable alternatives, the additional expense would be justified.

The next step from the feasibility of the SOTS-T configuration would be the construction and testing of a prototype on board an oil tanker.

Additional tanker environmental factors which could influence the prototype would be required to be monitored on board a tanker prior to testing. These would include noise level measurements in the cargo tanks during loading, transit, and unloading operations, impact measurement during tank washing cycles, and a determination of installation parameters. The final prototype would be required to be evaluated and approved intrinsically safe for on board testing.

APPENDIX A

LABORATORY DATA

TABLE A1

Attenuation in 200 Gallon Tank

Water

Distance[1] (inches)	200 kHz $V_{out(pp)}$	200 kHz db[2]	100 kHz $V_{out(pp)}$	100 kHz db[2]
12	0.97		0.40	
24	0.65	3.5	0.28	3.1
36	0.45	6.7	0.20	6.0
48	0.35	8.9	0.14	9.1
60	0.27	11.1	0.12	10.5
72	0.22	12.8	0.09	13.0

(1) Distance of Receiver from Transmitter

(2) Reference 12 inches

Input Voltage

200 kHz - 10 V_{pp}

100 kHz - 28 V_{pp}

TABLE A2

Attenuation in 200 Gallon Tank

#6 Fuel Oil

Distance[1] (inches)	200 kHz $V_{out(pp)}$	200 kHz db[2]	100 kHz $V_{out(pp)}$	100 kHz db[2]
12	1.36		0.31	
24	0.60	7.1	0.175	5.0
36	0.29	13.4	0.104	9.5
48	0.15	19.1	0.065	13.6
60	0.075	25.2	0.044	17.0
72	0.044	29.8	0.033	19.5

(1) Distance of Receiver from Transmitter

(2) Reference 12 inches

Input Voltage

200 kHz - 10 V_{pp}

100 kHz - 28 V_{pp}

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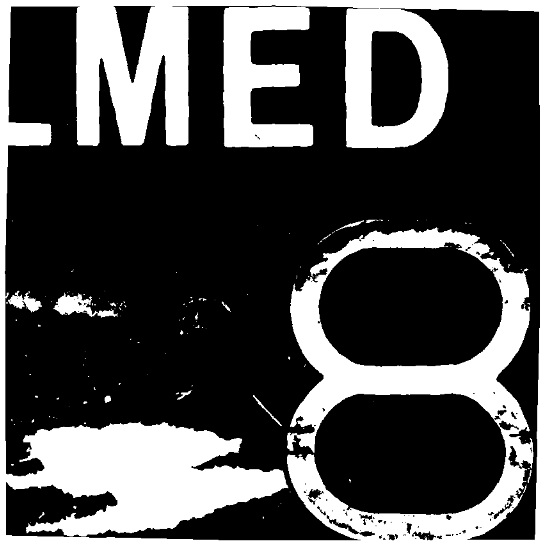
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